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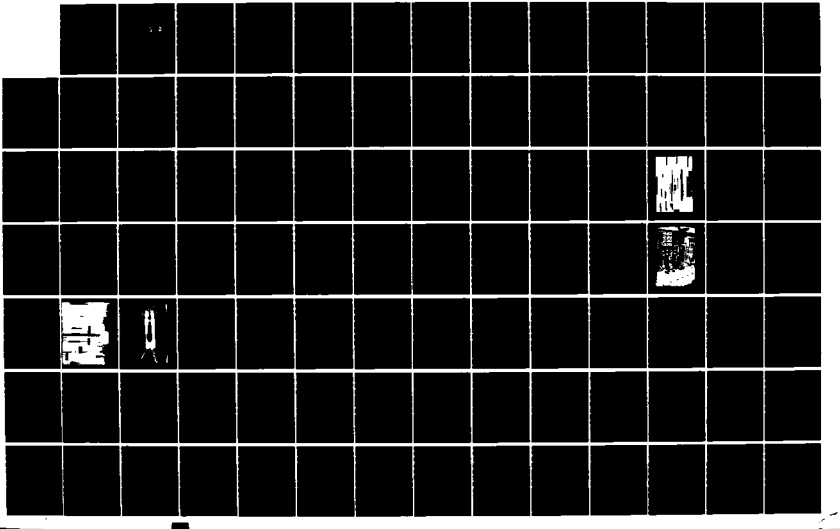

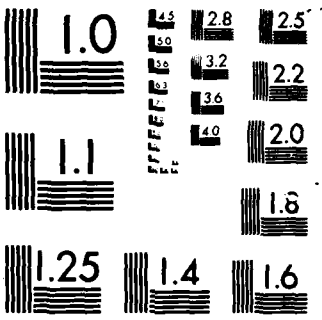

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FUEL PROCESSING SYSTEM FOR A 5kW METHANOL FUEL CELL POWER UNIT

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27 NOVEMBER 1985

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Reforming
Fuel Cell Power Plant
Phosphoric Acid Fuel Cell

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

This report documents the development and design of a 5kW neat methanol reformer for phosphoric acid fuel cell power plants. The reformer design was based on utilizing burner exhaust as the source of water required for reforming. This approach was arrived at after evaluation of several system options. A developmental unit was tested, and test data is documented indicating that all design objectives were met except for start-up time.

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SUMMARY

A 12-month project was conducted for the development of a methanol fuel processor to produce hydrogen fuel for a phosphoric acid fuel cell power unit. The fuel processor is based on steam reforming of the methanol using water vapor obtained by combustion of fuel cell stack anode tail-gas with ambient air. In contrast to conventional steam reformers, this approach avoids introduction of liquid water at the reformer inlet. Vaporizer heat requirements are reduced substantially, and water condenser and fuel premix equipment are eliminated.

Mass and energy balance calculations were performed for four candidate power unit system configurations. A preliminary fuel processor design was developed for use with the preferred power unit system design. The burner and vaporizer for the fuel processor were built and tested. Based on the results of these tests, a 5kW rated fuel processor design was developed and evaluated.

The fuel processor met the anticipated power unit requirements for fuel conversion efficiency and weight. Startup time was 30 minutes instead of the projected 15 minutes. The test results were used to generate a modified developmental design which projects improved start-up and system integration features.

PREFACE

This effort was conducted under the direction of Dr. Larry Christner, with advisory support from Dr. Baker, Dr. Maru, Mr. Abens and Dr. Farooque. The Program Manager was Mr. Steinfe l.

Material and energy balances, and systems evaluations w conducted by Dr. Ghezel-Ayagh. Experimental component des and specification was conducted by Mr. Gionfriddo. Test o erations, including fabrication, component assembly, gas anal ysis and data acquisition were conducted by Mr. Koehler.

Drafting and drawings were done by C. DeCarvalho and C. Hunt. Word processing and layout were done by M. Shanley and J. Muehlfeld. Technical editing was done by L. Rindner and J. Muehlfeld.

The cooperation and support of all the above people is appreciated and acknowledged in carrying out this effort.

The U.S. Army Belvoir R&D Center Project Manager was Mr. E. Starkovich.

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1.0 INTRODUCTION

The development of small methanol fuel cell power units has so far evolved with methanol-water mix as the fuel. Hydrogen for the fuel cell stack is generated by steam reforming of this fuel over a low temperature shift catalyst. This approach results in a simple power plant system design, but complicates fuel supply logsitics because of the need to mix the methanol with water. The mixed fuel also has a lower energy content, an important drawback for remote power applications.

Energy Research Corporation (ERC) has been pursuing approaches for operation of the fuel cell power unit on neat methanol. Recently, ERC completed acceptance testing of a 5kW neat methanol power unit built for the Air Force under Contract F33615-82-C-2201. In this power unit, water was recovered by condensation from the exhaust streams and mixed automatically in the required proportions with methanol prior to steam reforming. This approach was further developed by building and testing a 3kW neat methanol brassboard power unit for the U.S. Army under Contract DAAK70-79-C-0249.

This report describes a 12-month effort toward the development of an alternate approach to processing neat methanol in a fuel cell power unit. This approach is based on recirculation of combusted anode exhaust from the fuel cell stack to the reformer, eliminating the condenser and the fuel mixing tank. The scope of the project included:

- Overall fuel cell power unit system analysis.
- Conceptual design of the fuel processor.
- Design development of key fuel processor components.
- Fabrication of a complete 5kW rated fuel processor.
- Testing of the fuel processor with simulated fuel cell stack gas streams.

The minimum performance requirements and the achievements of the reformer established for this project are shown in Table 1.

TABLE 1.
NEAT METHANOL REFORMER SPECIFICATIONS

	REQUIRED	DESIRED	ACHIEVED
METHANOL CONSUMPTION (L/hr)			
Rated Load	7.75	4.0	4.7
50% Rated Load	7.75	2.0	2.5
WEIGHT (Kg)	114	50	31
STARTUP TIME (min)	15	5	30
METHANOL FUEL QUALITY	OM 232	OM 232 with 5% higher alcohols or hydrocarbons	OM 232
PRODUCT GAS QUALITY			
% H_2, minimum	25	25	26.9
% CO	<3	<1	0.8

2.0 POWER UNIT SYSTEM CONFIGURATION

The development of a fuel processor that can operate on neat methanol was initiated by evaluation of various options in fuel cell power unit system configuration. Among the options available, two categories can be identified:

- Water recovery by condensation
- Water recovery by vapor recycle

The second category was chosen for this effort because it requires no condenser or liquid water metering. The water needed for reforming is provided by recycling water vapor available in stack exhaust gases and by partial oxidation of methanol. Four possible power unit system configurations were evaluated:

System #1 - Partial Oxidation with Air
System #2 - Cathode Exhaust Recycle
System #3 - Cathode and Anode Exhaust Recycle
System #4 - Anode Exhaust Recycle and Air

These systems are illustrated in Figures 1 and 2, and their key features are summarized in Table 2.

System #1 requires no recycle and obtains water by the partial oxidation of methanol. This is the simplest, but least efficient system because methanol is combusted to generate water for reforming. The unused anode hydrogen and moisture in the stack exhaust are not utilized.

System #2 utilizes the cathode exhaust to provide oxygen for partial oxidation of methanol and recycles some of the moisture in the cathode exhaust. The anode exhaust hydrogen again is not utilized. This system is more efficient than System #1, but requires a recycle blower on the cathode exhaust, and a means to control the flow rate of the recycled gas.

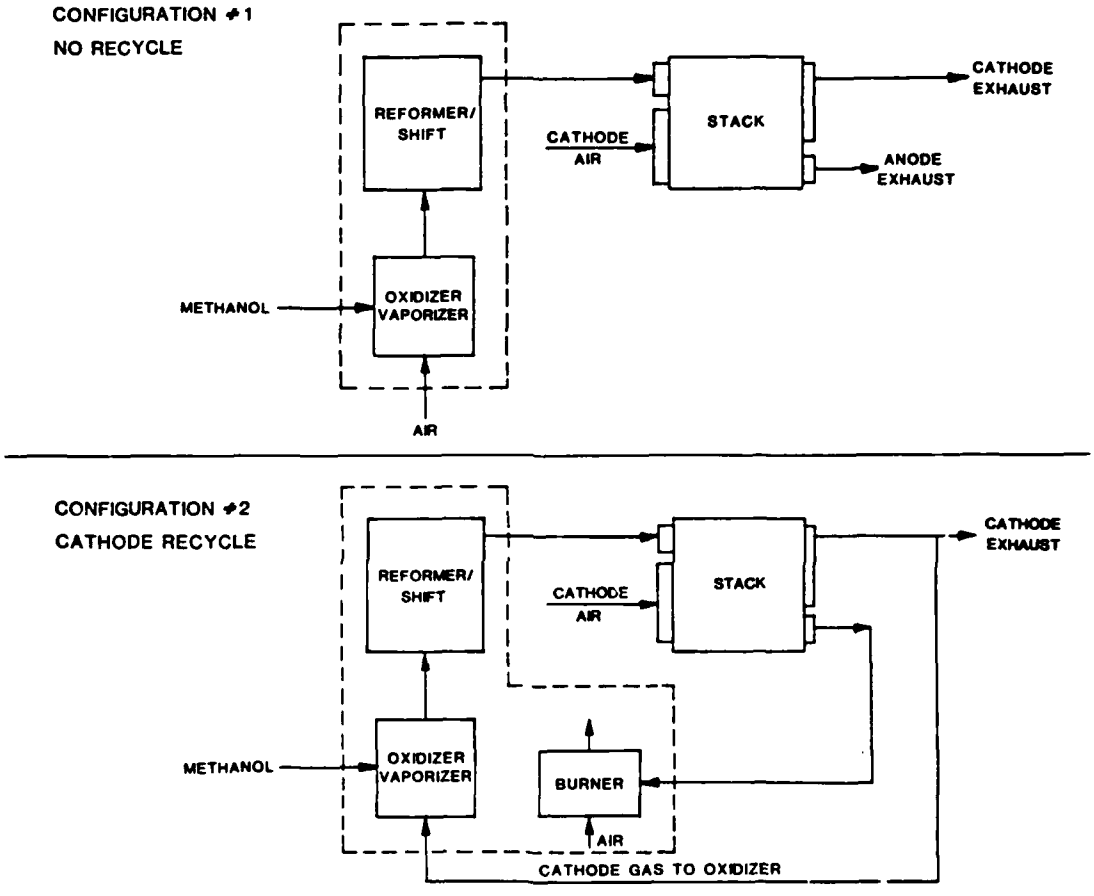


FIGURE 1.
SYSTEM CONFIGURATIONS 1 and 2

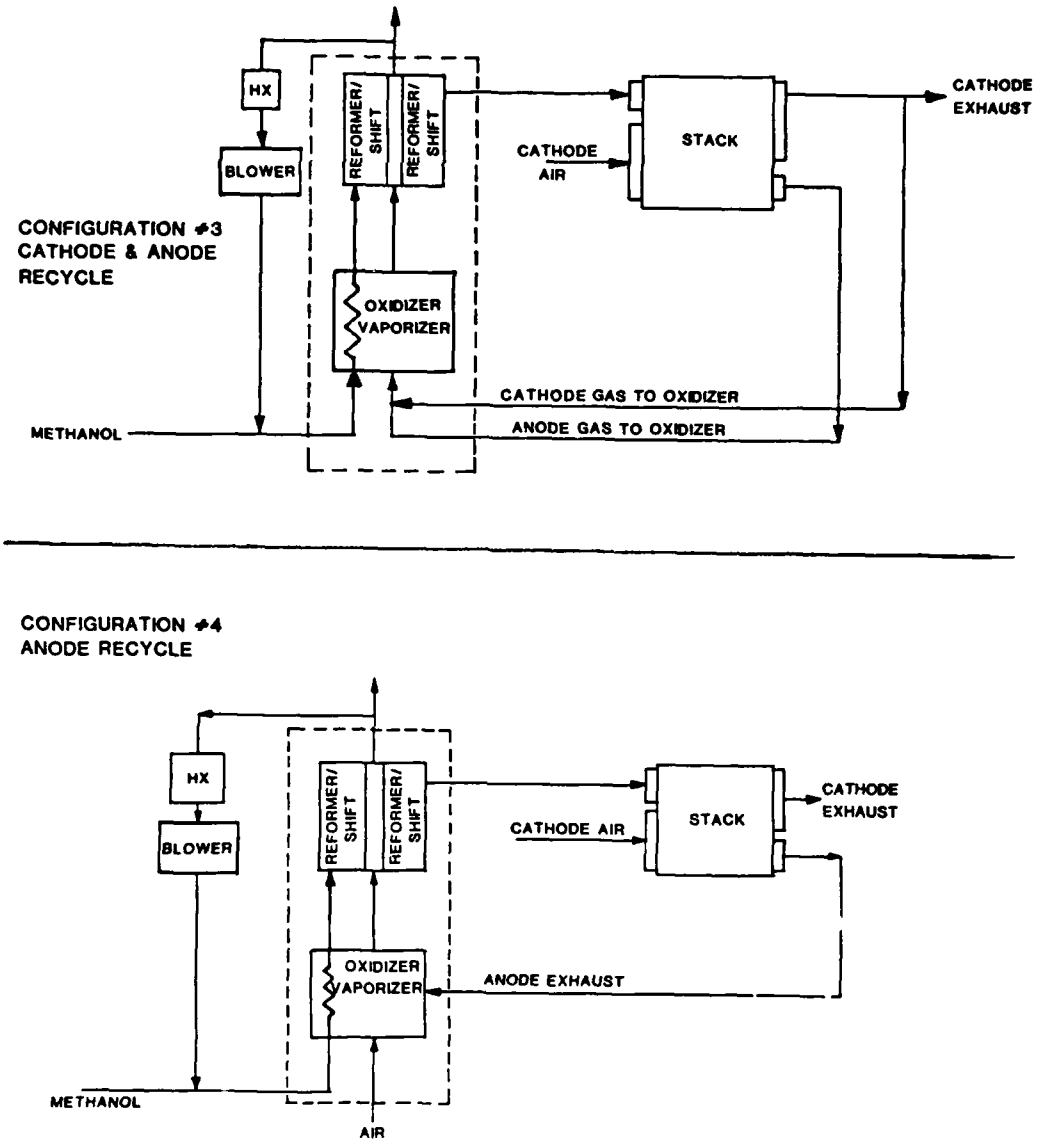


FIGURE 2.

SYSTEM CONFIGURATIONS 3 and 4

TABLE 2

SYSTEM CONFIGURATION OPTIONS

SYSTEM	FEATURES	EFFICIENCY	COMPLEXITY
1	No recycle Air Oxidation	Low	Low
2	Cathode Recycle	Medium	Medium
3	Cathode & Anode Recycle	Highest	High
4	Anode Recycle and Air Oxidation	High	Medium

System #3 recycles both anode and cathode exhausts, and as a result obtains the highest efficiency. In this configuration, anode exhaust is burned using the oxygen in the cathode exhaust. The product water is utilized in the reformer by recycling the combusted anode exhaust. This configuration requires recycle blowers on anode and cathode streams and a flow split of the cathode exhaust making the system more complicated to control.

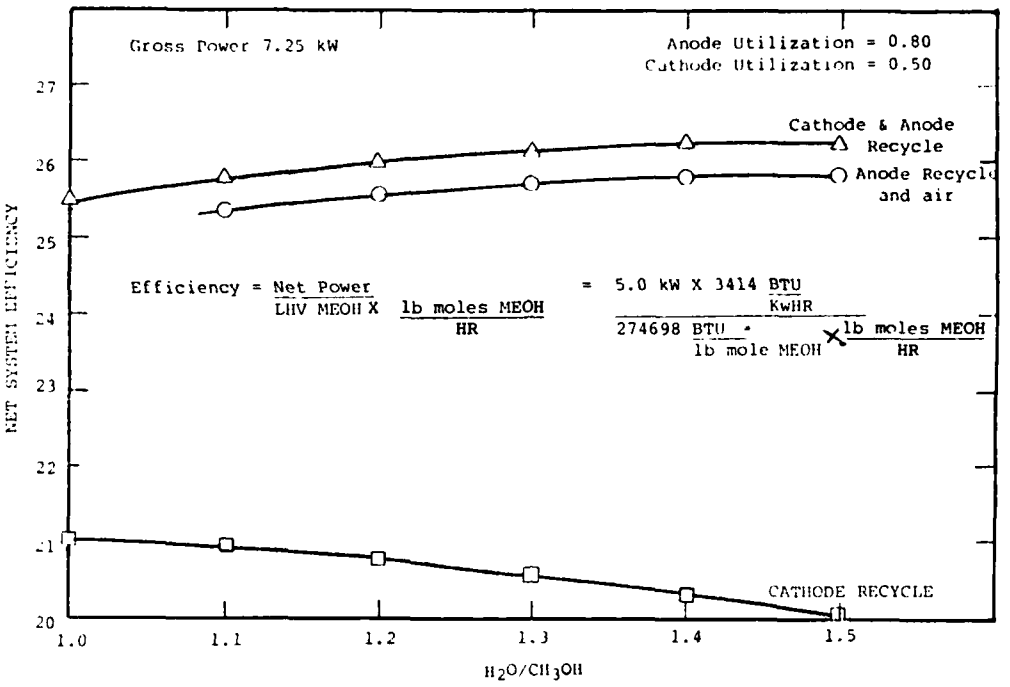
The elimination of the cathode recycle from System #3 results in a simpler system design with a minimum loss of efficiency. This system (System #4) was adopted as the basis for the 5kW reformer development.

Relative efficiencies of Systems #2, #3, and #4 are shown in Figure 3. System #2, with cathode recycle, results in the lowest efficiency, which declines with increasing H_2O/CH_3OH ratio since more CH_3OH is oxidized to obtain higher H_2O/CH_3OH ratios, leaving less CH_3OH to be reformed to hydrogen.

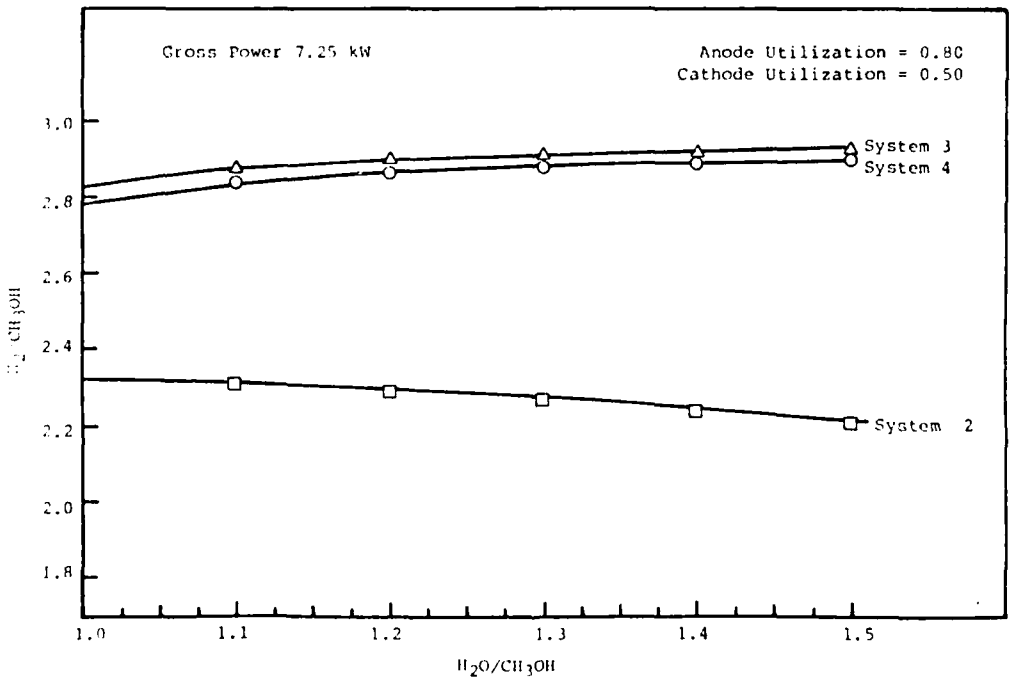
Systems #3 and #4 show significantly higher efficiencies because water is derived by combusting anode exhaust hydrogen, rather than methanol. System #3 shows slightly higher efficiencies than System #4 due to the moisture utilized from the cathode recycle. However, System #4 is simpler to control since the cathode stream is decoupled from the fuel processor.

Of the four options evaluated, System #4 appears to be most attractive because of:

- Relative simplicity of operation and control,
- High efficiency,
- Achievement of thermal balance with high anode fuel utilization.



NET SYSTEM EFFICIENCY



HYDROGEN PRODUCTION

FIGURE 3.

3.0 FUEL PROCESSOR CONCEPT DEVELOPMENT

The fuel cell power unit system chosen for development is System #4 and is enlarged in Figure 4, for clarity. The fuel processor is defined within the dotted line. This system operates on anode exhaust and air. A portion of the burner exhaust is recycled to provide the water for reforming.

The fuel processor concept was developed based on the following key criteria:

- 75% anode fuel utilization in the stack at full load
- 65% anode fuel utilization in the stack at part load (idling condition)
- Constant recycle blower speed for all load conditions

Design basis operating conditions are shown in Table 3.

3.1 HEAT BALANCE

Figure 5 shows the heat balance for the reformer and the heat duty for the recycle heat exchanger at anode fuel utilizations of 75% and 80%. At 75% anode utilization and a H_2O/CH_3OH ratio of 1.22, the excess heat in the reformer will be 5500 BTU/hr. This heat will be lost to the surroundings. The recycle heat exchanger at the same conditions will require a heat load of 2700 BTU/hr.

Figure 6 indicates that at part load conditions, (4 kW stack) the excess heat in the reformer will be 4590 BTU/hr at an anode fuel utilization of 65% and a H_2O/CH_3OH mol ratio of 2.28. This indicates that a heat balance can be maintained as the load varies from full load to part load conditions. In order to reduce control requirements, constant recycle blower speed was chosen.

CONFIGURATION # 4

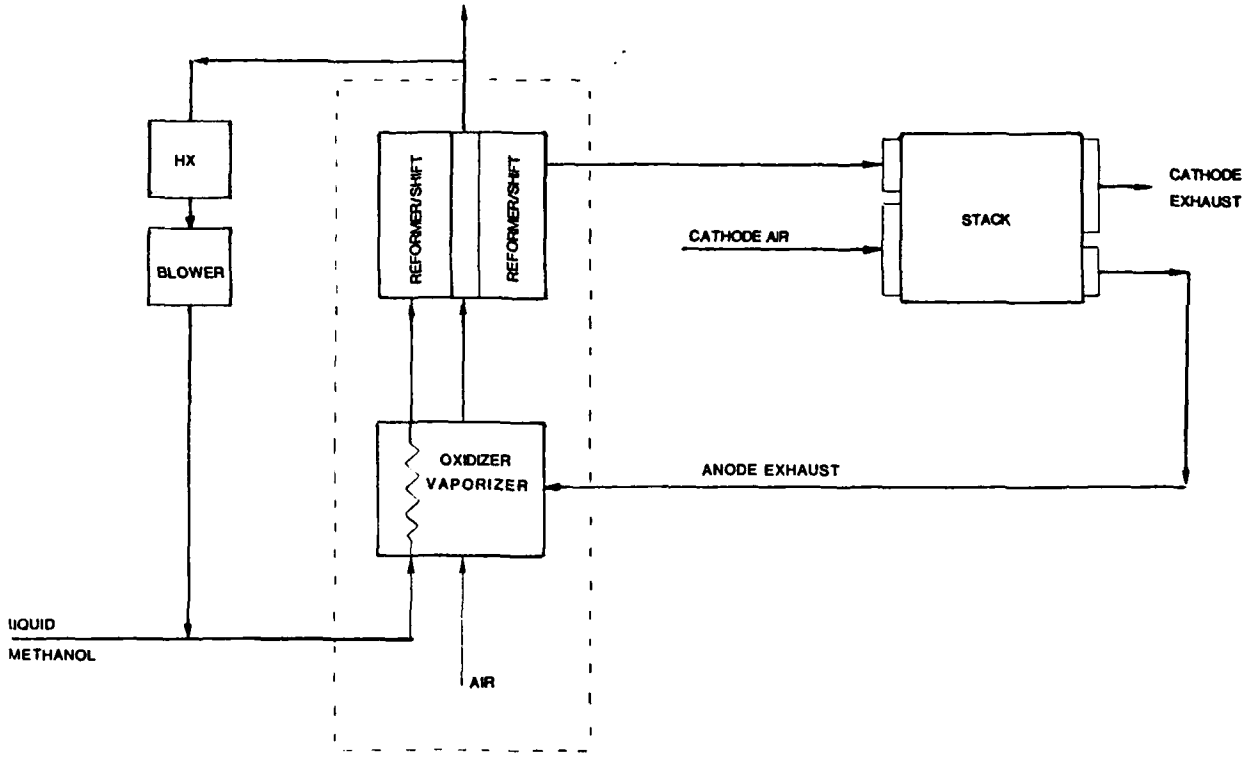


FIGURE 4.
5kW NEAT METHANOL FUEL PROCESSOR SYSTEM

TABLE 3.

5kW NEAT METHANOL FUEL PROCESSOR
DESIGN BASIS-OPERATING CONDITIONS

STACK OUTPUT, kW	7.25	4.0
Anode Utilization, %	75	65
Cathode Utilization, %	50	50
H_2O/CH_3OH at Reformer Inlet	1.22	2.28
Reformer Heat Load, (BTU/Hr)	5479	4590
HX Heat Load	2700	2643
Recycle Gas Flow Rate (Actual Ft^3/Hr)	894	892
Product H_2 Concentration, %	31	19.9
CO Concentration, %	1.3	.3
Fuel Flow, LB/Hr	8.16	4.35
Oxidizer Air Flow, SCFH	195	135

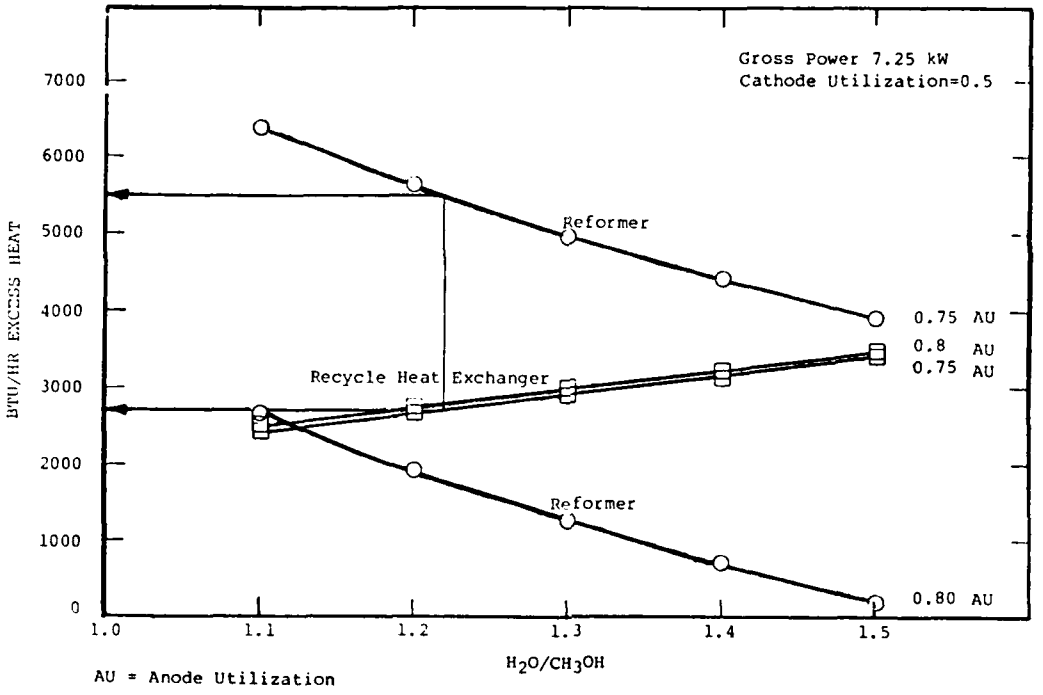


FIGURE 5.
REFORMER AND RECYCLE HEAT EXCHANGER HEAT BALANCE

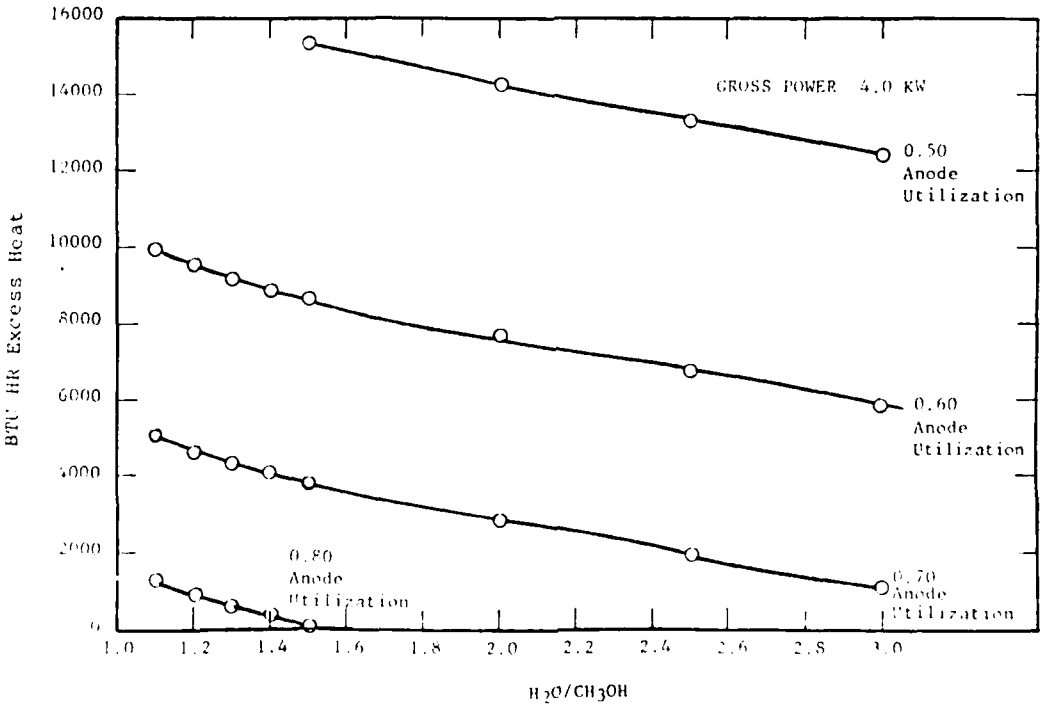


FIGURE 6.
REFORMER HEAT BALANCE AT PART LOAD

Figure 7 indicates that the H_2O/CH_3OH mol ratio increases as the load decreases. At rated load, the water to methanol mol ratio is 1.22:1.

3.2 AIR AND FUEL REQUIREMENTS

Air and fuel requirements of the fuel processor are shown in Figures 8 and 9. The hydrogen concentration in the fuel gas to the anode is shown in Figure 10. The curves indicate that higher H_2O/CH_3OH mol ratios and higher anode utilizations produce lower H_2 concentrations. This is due to dilution by the recycle gas as H_2O/CH_3OH mol ratio is increased by increasing the recycle flow rate. The equilibrium CO concentrations are reduced by increasing H_2O/CH_3OH mol ratio due to the CO shift reaction and the diluting effect of the recycle gas as seen in Figure 11. Figure 12 demonstrates the recycle heat exchanger heat duty at part load, and Figure 13 shows the recycle blower flow rate at full load.

3.3 CONFIGURATION AND OPERATION

The conceptual design of the fuel processor is shown in Figure 14. Stack anode exhaust is combusted with air over a platinum catalyst in the center annulus to heat the middle annulus where methanol is vaporized. A portion of the combustion product is recycled back into the vaporizer annulus which contains a stainless steel wick material for absorbing the liquid methanol. The catalyst bed is in the outermost annulus and is heated by heat transfer from the vaporizer and by the sensible heat of the incoming gases. The top of the bed is cooled by the inlet of the vaporizer section to minimize CO and maximize H_2 production. The dimensions and weights estimated for this processor design are summarized in Table 4.

3.4 MATERIAL AND ENERGY BALANCES

Material and energy balances were conducted for a number of operating parameters to determine their effect on the per-

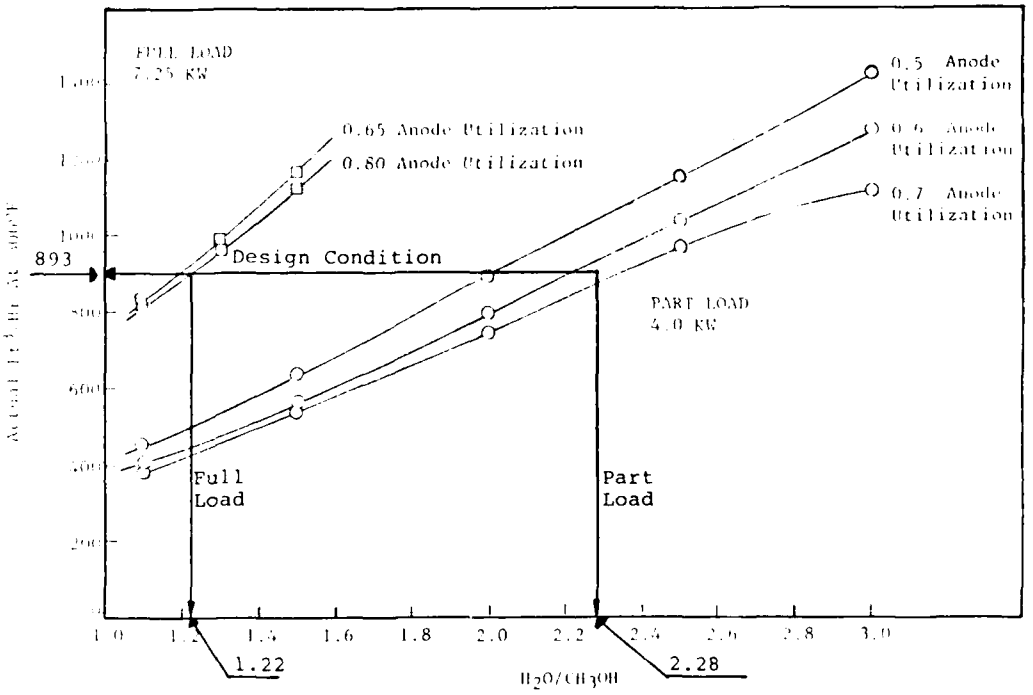


FIGURE 7.

RECYCLE BLOWER FLOW RATE AT FULL LOAD AND PART LOAD CONDITIONS

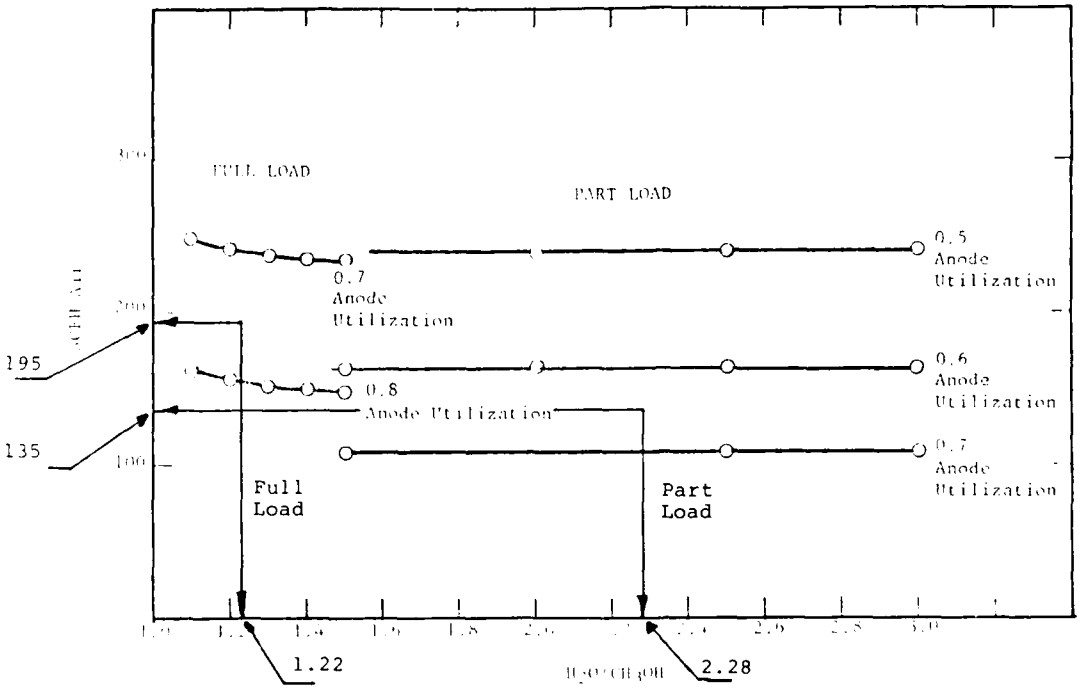


FIGURE 8.
AIR REQUIRED FOR COMBUSTION OF ANODE EXHAUST

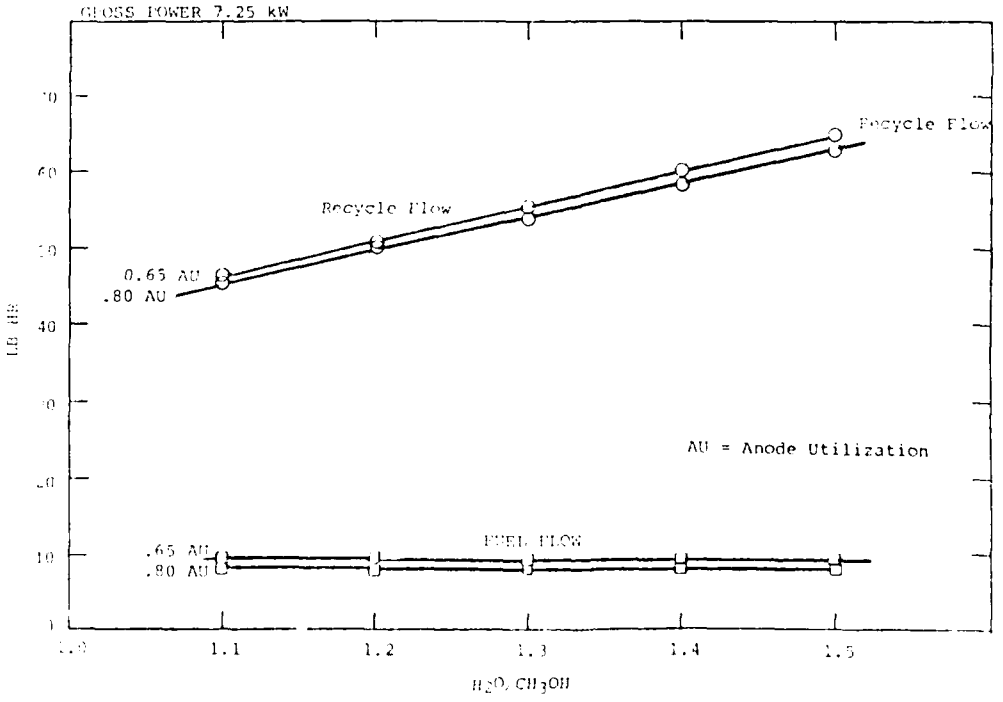


FIGURE 9.
RECYCLE AND FUEL FLOWS AT FULL LOAD

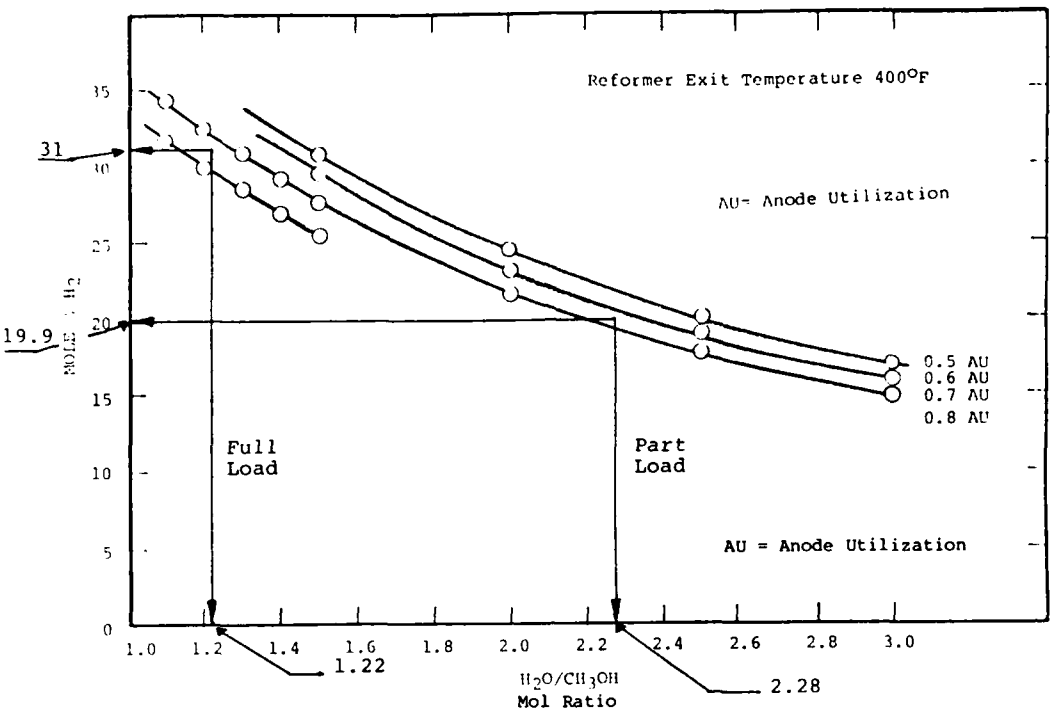


FIGURE 10.
HYDROGEN CONCENTRATION AS A FUNCTION OF H_2O/CH_3OH MOL RATIO

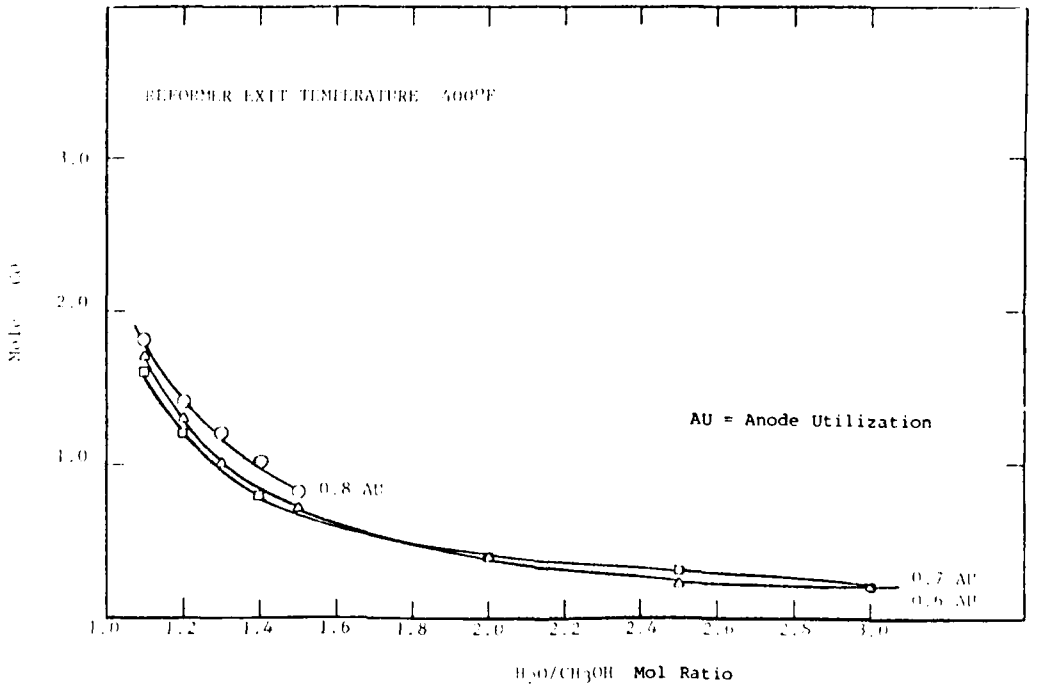


FIGURE 11.
CO CONCENTRATION AS A FUNCTION OF H_2O/CH_3OH MOL RATIO

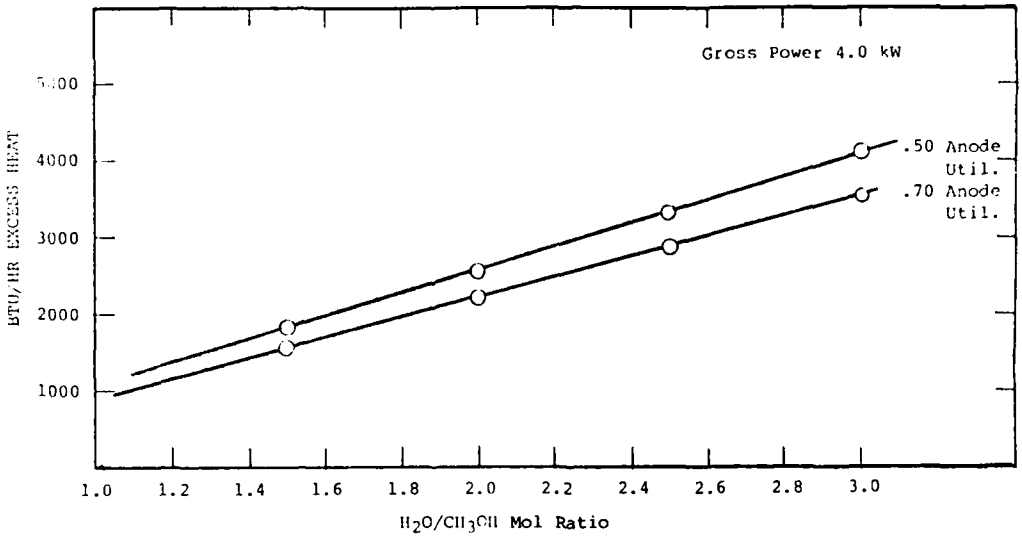


FIGURE 12.
RECYCLE HEAT EXCHANGER AT PART LOAD

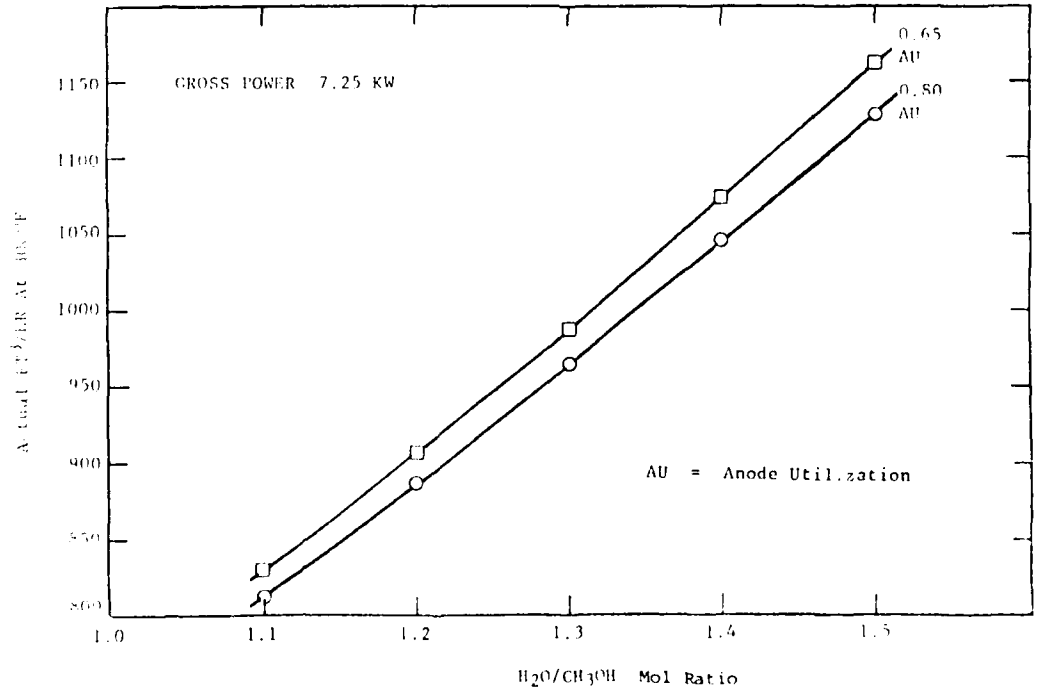


FIGURE 13.
RECYCLE BLOWER FLOW RATE AT FULL LOAD

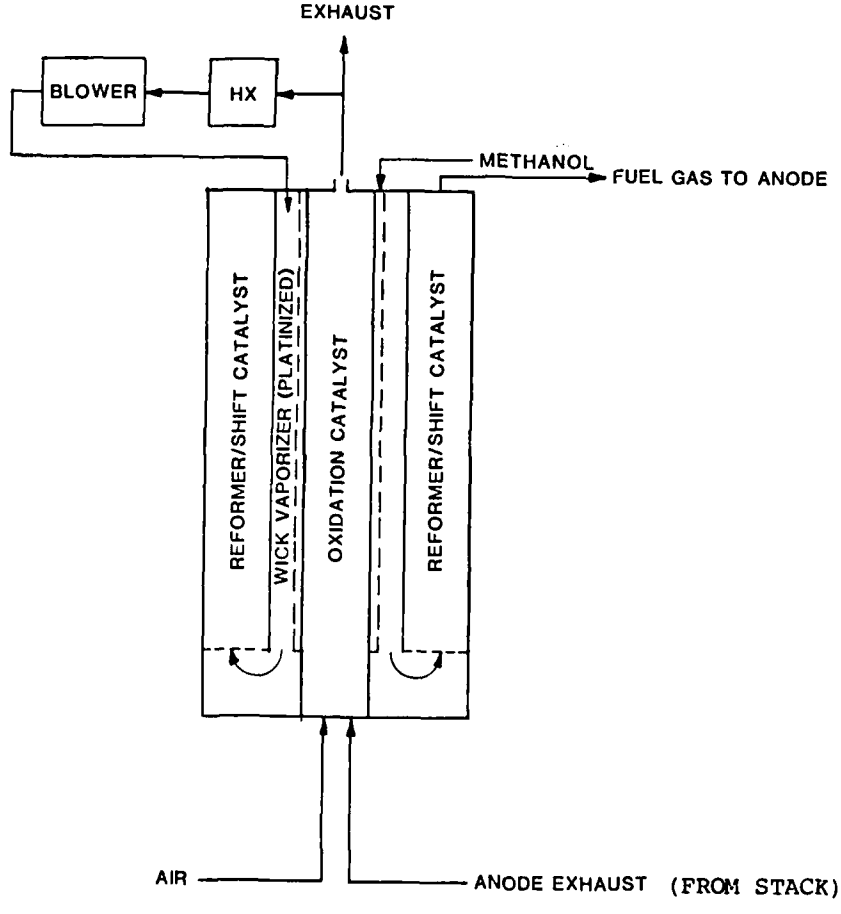


FIGURE 14.
5kW FUEL PROCESSOR CONCEPTUAL DESIGN

TABLE 4.

5kW NEAT METHANOL FUEL PROCESSOR
CONCEPTUAL DESIGN

Overall Length	24 inches
Overall Diameter (without insulation)	5 9/16 inches
Catalyst Volume	0.20 ft^3
GHSV[1] at Reformer Inlet	3500
Catalyst Loading	11.97 Lbs
Estimated Weight	75 Lbs.

[1] GHSV at inlet based on gas volume at 60°F and 760 mm H_g pressure.

formance of the overall system. The key parameters of the material and energy balance are shown in Table 5. The complete node array analysis for the system is given in Appendix A. The baseline design compositions and flow rates at full load are shown on page A-3. Baseline design compositions and flow rates at part load are shown on page A-4.

TABLE 5.

MATERIAL AND ENERGY BALANCE CONDITIONS

	CONDITIONS EVALUATED		
PARAMETER	FULL LOAD (7.25 kW) GROSS POWER	PART LOAD (4.0 kW) GROSS POWER	FULL LOAD DESIGN CONDITION CHOSEN
Anode Utilization	.65, .70, .75 .80	.65	.75
Cathode Utilization	.50	.50	.50
H_2O/CH_3OH At Reformer Inlet	1.1, 1.3, 1.5	2.28	1.22
Anode Exhaust Combustion Air	Stoichiometric	Stoichiometric	Stoichiometric

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4.0 PRELIMINARY FUEL PROCESSOR DESIGN

The preliminary fuel processor design was based on the system analysis and the material and energy balance. The key components of the fuel processor are:

- a combustion tube for oxidation of anode exhaust
- a methanol vaporizer
- a reforming/shift catalyst bed

4.1 COMBUSTION OF ANODE EXHAUST

The approach chosen for this design was to use catalytic combustion utilizing platinum catalysts only. Catalytic combustion can be efficient at low excess air levels, possibly approaching stoichiometric. This would increase adiabatic flame temperatures and reduce the work load of the combustion air blowers.

Based on previous subscale testing, the combustion tube was sized at 1 1/4 inch diameter and 24 inches long. The platinum catalyst chosen for the combustion tube was a spiralled platinum monolith.

4.2 VAPORIZATION OF METHANOL

The vaporizer design for this fuel processor includes a wick vaporizer. The wick vaporizer was tested and used in subscale boilers and reactors in previous work and was found to operate smoothly. The advantage of the wick vaporizer is that it spreads the liquid over a large surface area for good heat transfer. The wick material can be catalyzed thereby promoting some catalytic decomposition of methanol and hydrogen production in the vaporizer. This takes some of the reforming load off the catalyst bed, easing the heat requirements in the reforming zone.

Wick temperatures were used to determine at what point along the wick all of the liquid was vaporized. In single tube tests it was found that generally all the methanol was vaporized within one inch of the inlet. The wick material keeps the liquid against the heated surface resulting in good heat transfer and rapid, smooth vaporization.

4.3 REFORMING/SHIFT CATALYST BED

The size of the catalyst bed was determined from previous experience with the Army 3 kW power plant (Contract DAAK70-C-79-0249), and was scaled up directly. The preliminary design was specified as follows:

Catalyst Volume:	0.2 Ft^3
Catalyst Loading:	11.97 Lbs.
Catalyst:	UCI T2107 RS

The chemical and physical properties of the catalyst are shown in Table 6.

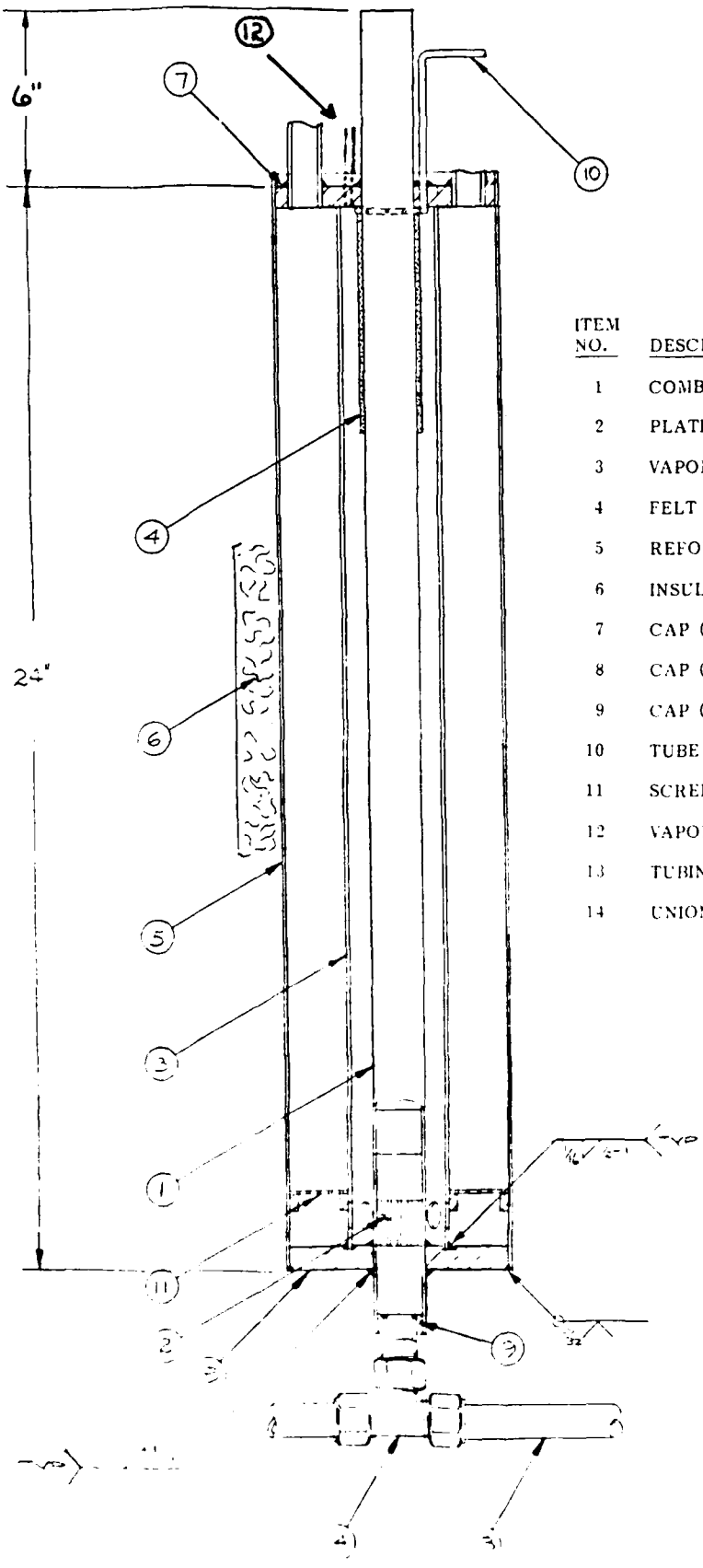
Figure 15 depicts the preliminary fuel processor design and Figure 16 shows a photograph of various components of the fuel processor.

TABLE 6.

TYPICAL CHEMICAL AND PHYSICAL PROPERTIES
OF UCI T2107 CATALYST

Chemical Composition	Weight % (Oxide Basis)
CuO	43.0 ± 4.0
ZnO	20.0
Al_2O_3	30.0
Cr_2O_3	3.2 ± 0.4
S	<0.05

Physical Properties	
A. Bulk Density, lbs./cu.Ft.	70 ± 5
B. Surface Area, m^2/g	130 ± 30
C. Pore Volume, cc/g	0.25 - 0.35
D. Crush Strength, lbs. DWL	10 minimum
E. Form	1/8"x1/8" tablets



ITEM NO.	DESCRIPTION
1	COMBUSTION TUBE
2	PLATINUM MONOLITH
3	VAPORIZER TUBE
4	FELT WICK 7" LONG
5	REFORMER TUBE
6	INSULATION
7	CAP (Reformer Exit)
8	CAP (Reformer Inlet)
9	CAP (Combustion Tube Inlet)
10	TUBE (Vaporizer Methanol Inl.)
11	SCREEN (Perforated)
12	VAPORIZER GAS. INLET
13	TUBING
14	UNION TEE

FIGURE 15.
PRELIMINARY FUEL PROCESSOR DESIGN

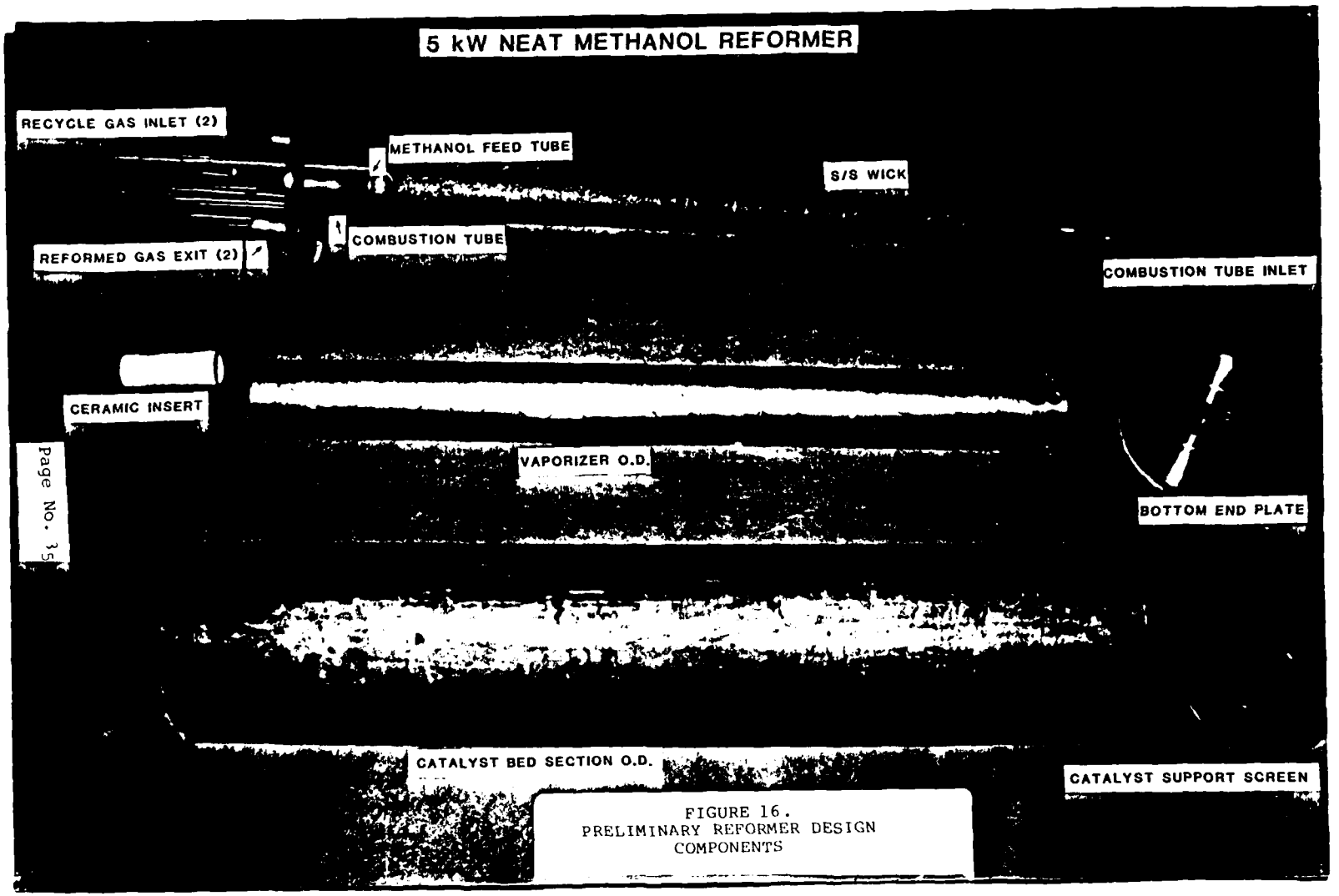


FIGURE 16.
PRELIMINARY REFORMER DESIGN
COMPONENTS

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5.0 COMPONENT TESTING

The preliminary design described in Section 4.0 was first evaluated by testing the combustor and vaporizer as separate components. The test facility flow schematic for the complete fuel processor is shown in Figure 17. The gas composition required was arrived at by metering the required amount of CH_3OH, H_2O, CO_2 N_2, H_2 and air, and preheating the mixture to the required temperature. Instrumentation included thermocouples, pressure gauges, pressure differential gauges, and gas flow meters. Gas composition was determined by gas chromatography. Test conditions were defined at full load (7.25 kW) and part load (4 kW) reactant flows.

5.1 COMBUSTION TUBE

Figure 18 illustrates the test configuration for combustion tube testing. Tests at 4 kW (idle power) flows indicated that the maximum bed temperature achieved was 1010°F, and the maximum wall temperature was 1026°F. Hydrogen combustion was 93.4% complete, and oxygen was 94.9% consumed, using stoichiometric air.

At full load flows, complete hydrogen combustion was achieved with 16.3% excess air. Maximum bed temperature was 1165°F and maximum tube wall temperature was 1146°F. Without excess air at full load conditions, the inlet wall temperature was reduced by about 30°F, and the exhaust gas contained 0.17% H_2. Figures 19 to 23 depict combustion tube temperature profiles and exhaust gas compositions for part load and full load flows.

The pressure drop in the combustion tube was 67-84 inches of water (part load and full load conditions). A larger diameter tube was used in the subsequent design to reduce the pressure drop.

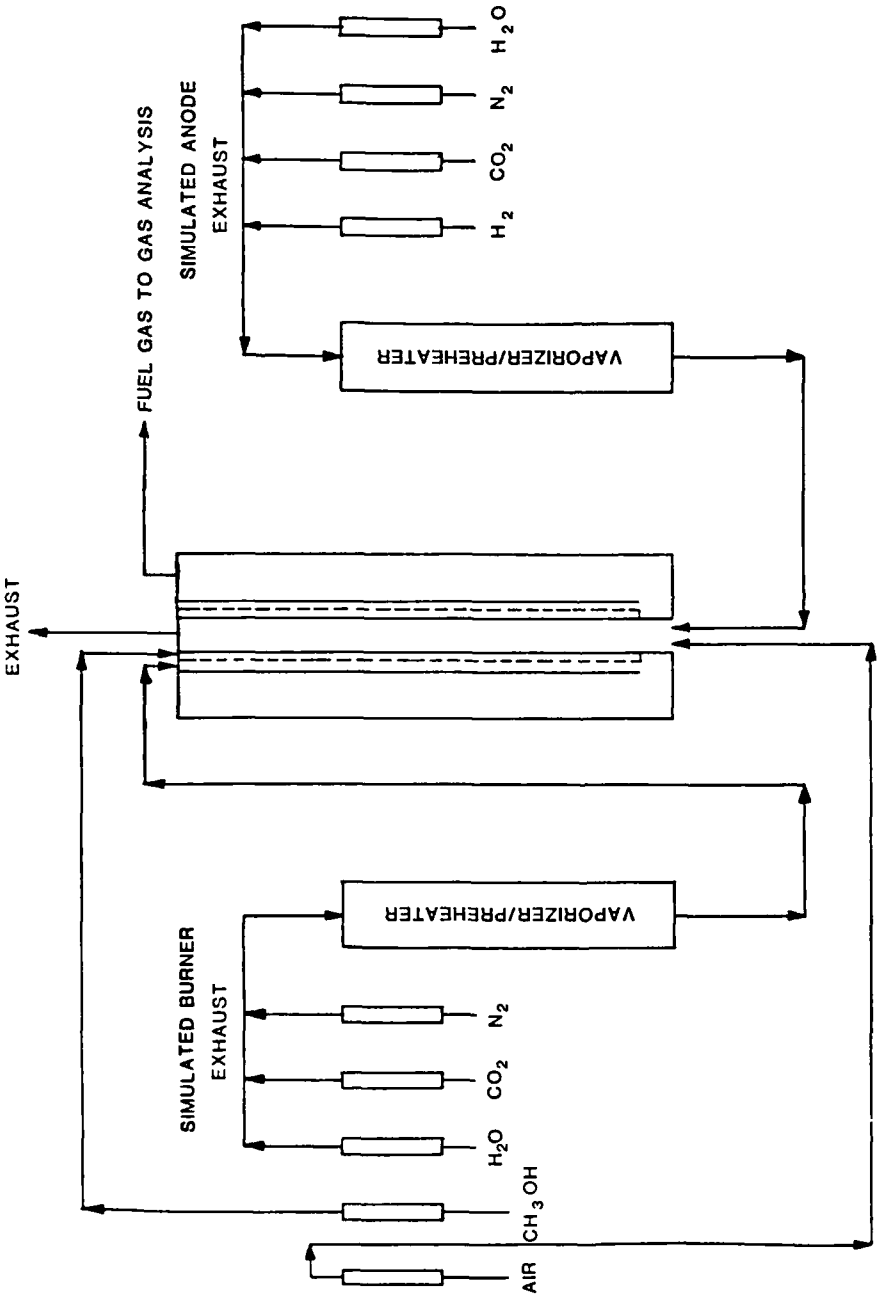

FIGURE 17.
5kW FUEL PROCESSOR FLOW SCHEMATIC IN TEST STAND CONFIGURATION

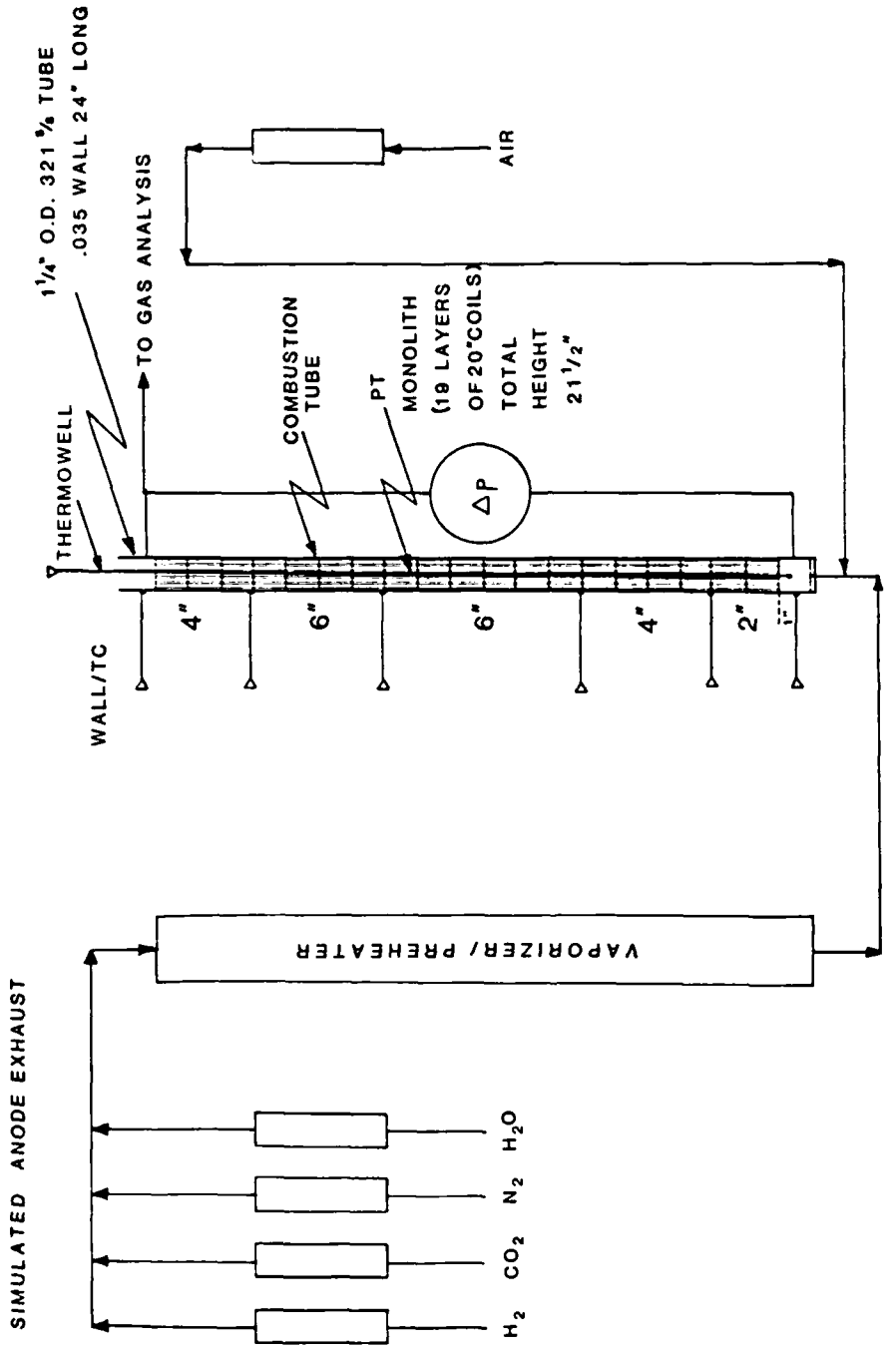

FIGURE 18.
COMBUSTION TUBE TESTING - 5kW NEAT METHANOL REFORMER

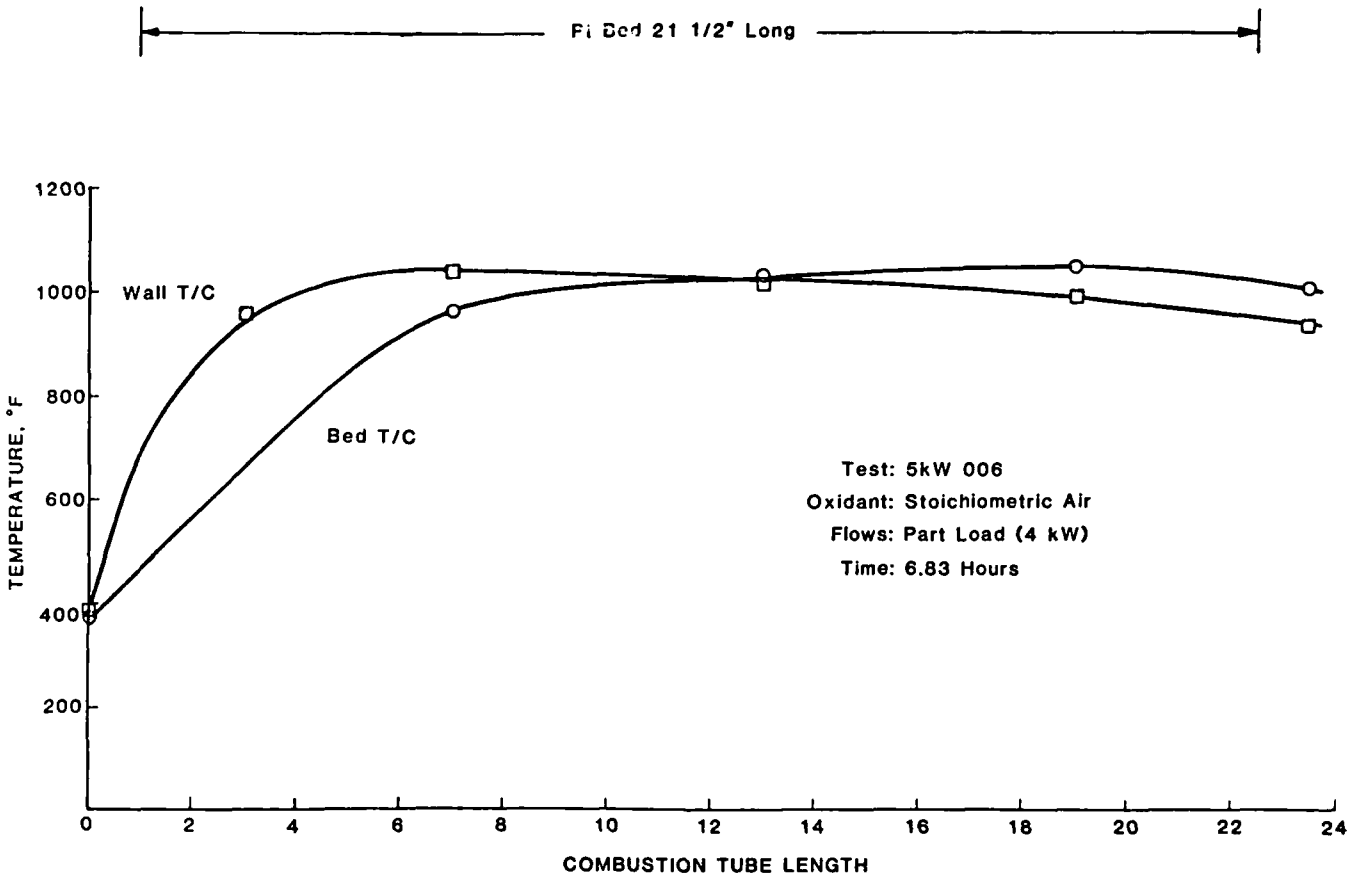

FIGURE 19.

COMBUSTION TUBE TEMPERATURE PROFILE - PART LOAD

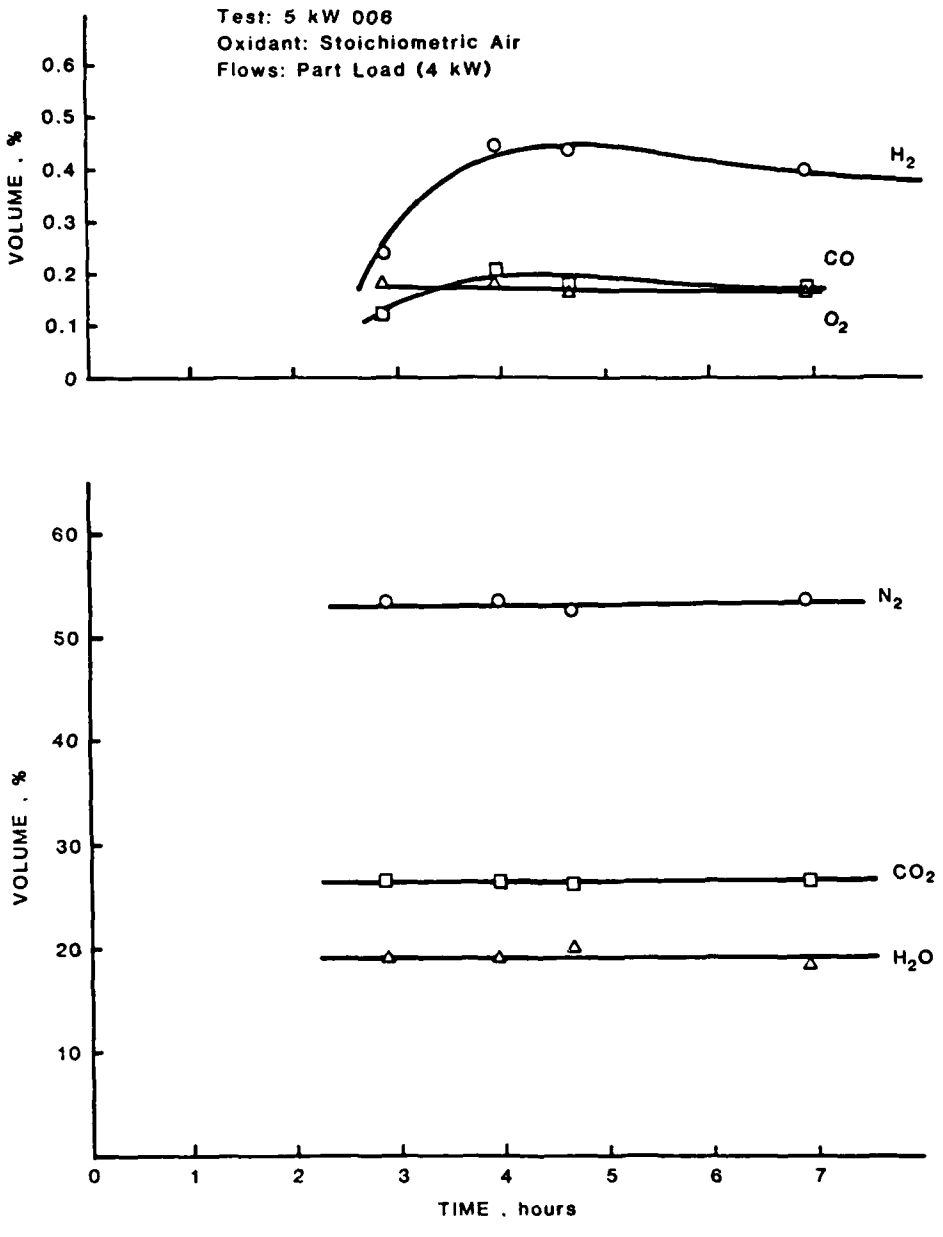

FIGURE 20.

COMBUSTION TUBE EXHAUST GAS COMPOSITIONS - PART LOAD

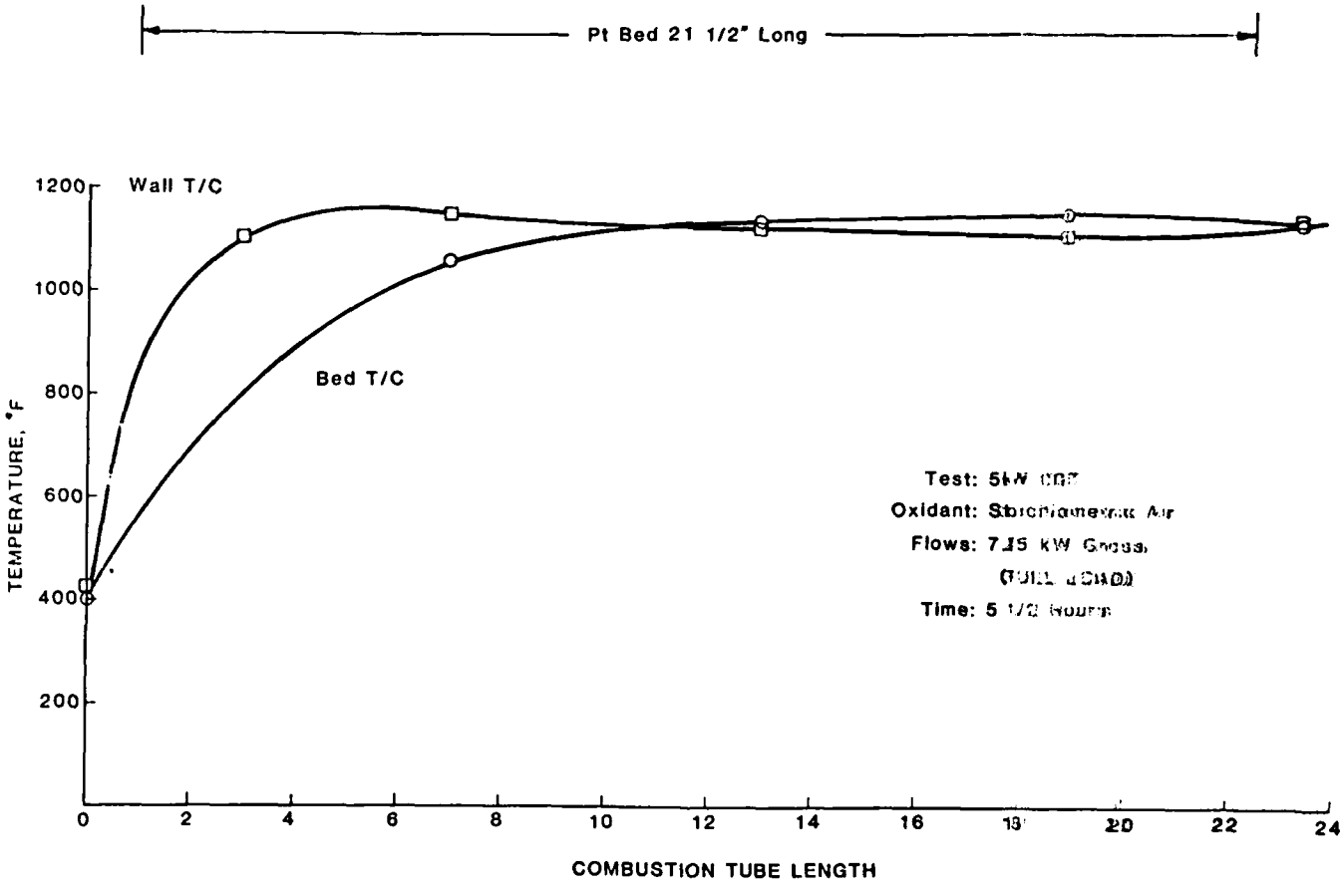

FIGURE 21.
COMBUSTION TUBE TEMPERATURE PROFILE - FULL LOAD

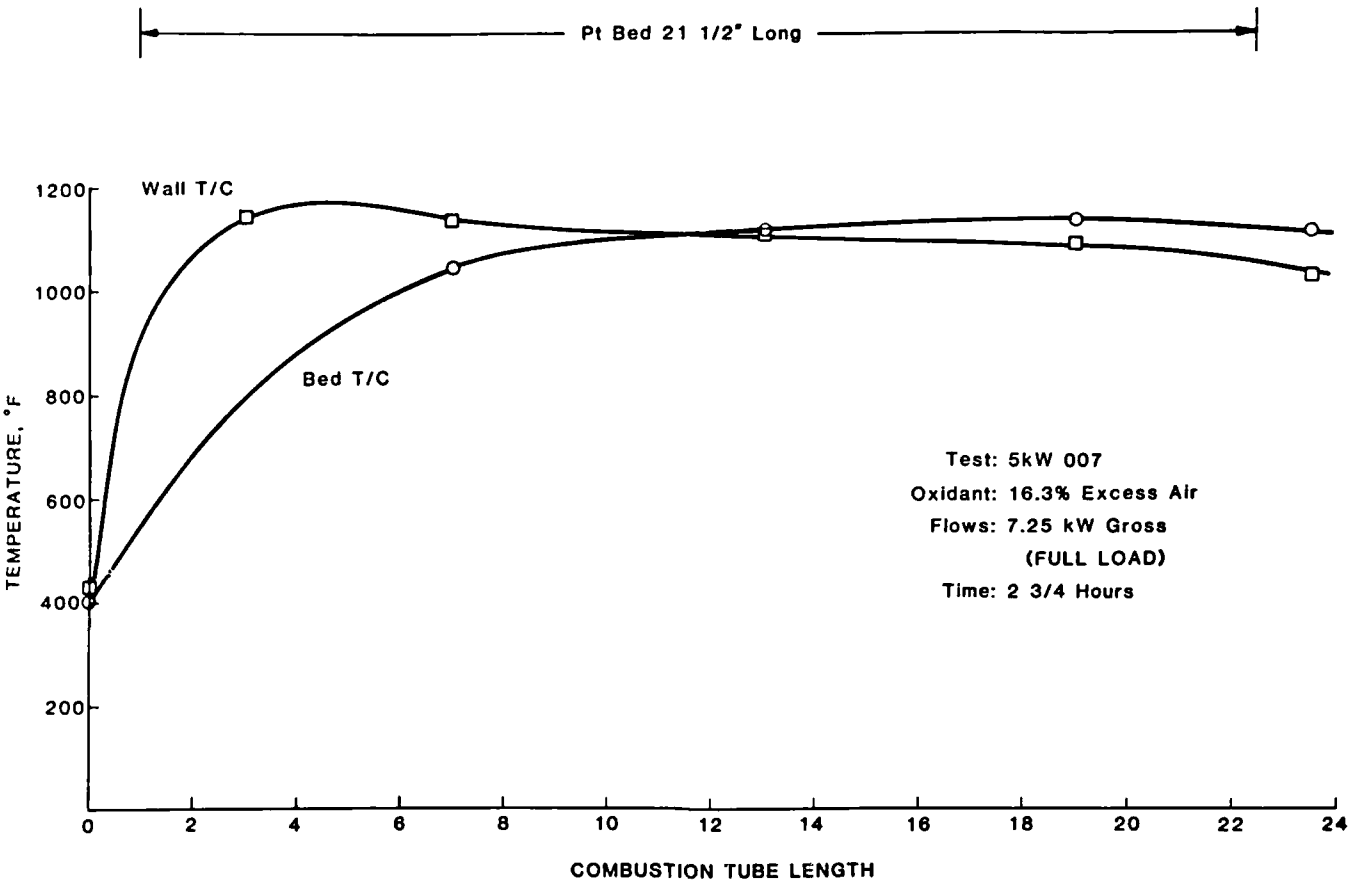

FIGURE 22.

COMBUSTION TUBE TEMPERATURE PROFILE - FULL LOAD AND EXCESS AIR

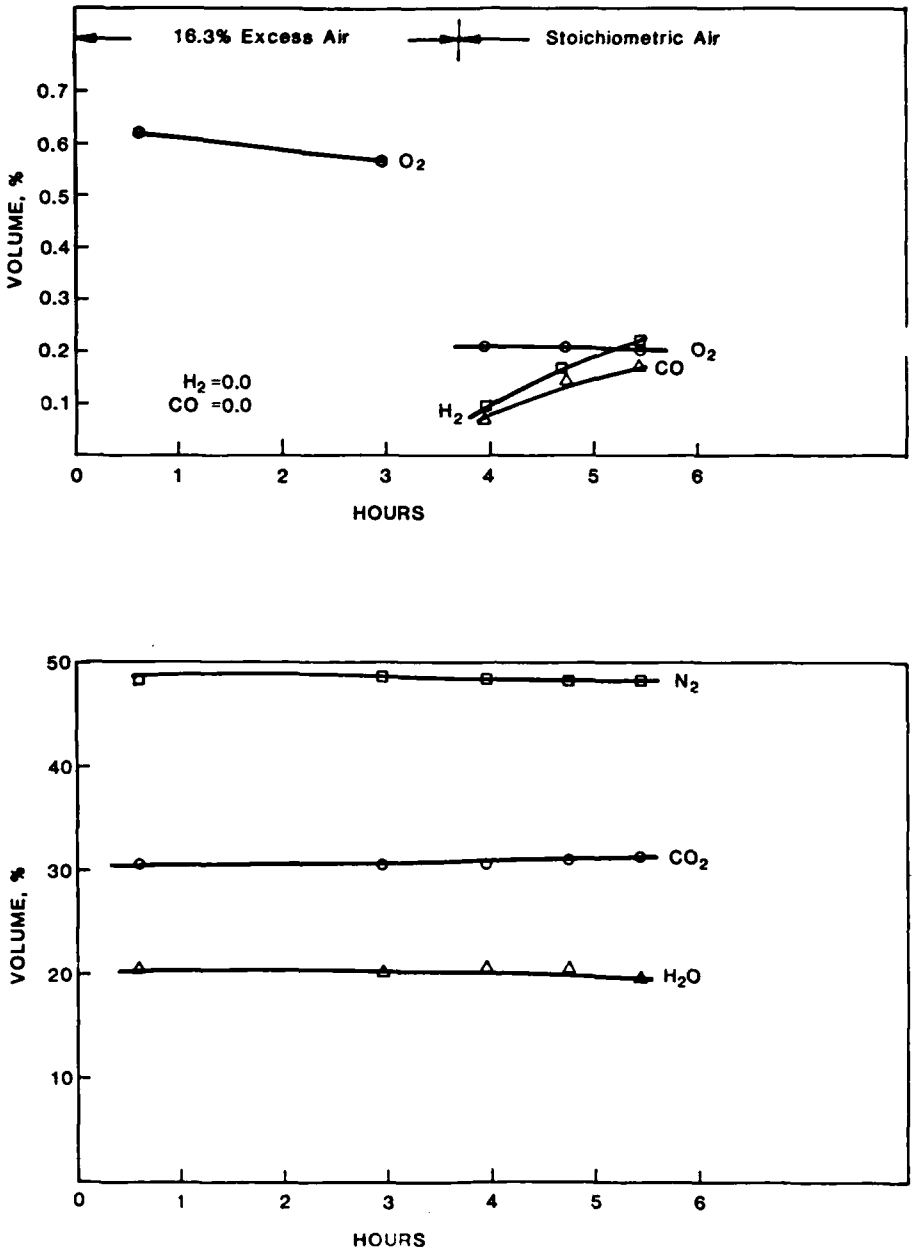

FIGURE 23.
COMBUSTION TUBE EXHAUST GAS COMPOSITION FULL LOAD

5.2 METHANOL VAPORIZER

Figure 24 illustrates the vaporizer tested. Tests were conducted at part load (4.36 lb/hr flow) and full load (8.17 lb/hr flow). In both cases all the methanol was vaporized within the first inch of the wick. The wick vaporizer appeared to function smoothly, and resulted in very rapid vaporization of the methanol. Temperature profiles in the vaporizer and combustion tube are shown in Figures 25 and 26. A photograph of the vaporizer mounted in the test facility is shown in Figure 27.

Although vaporization of the methanol was accomplished effectively in the wick vaporizer tested, the temperature of the fuel gas leaving the vaporizer was not as high as desired because of heat transfer limitation between the combustion tube and the vaporizer.

The heat duty required for heat transfer from the combustion tube to the vaporizer is 9072 BTU/hr. The actual heat transfer obtained was 2961 BTU/hr. Therefore, an increase in heat transfer by a factor of 3 was required. This necessitated a design modification which provided the additional heat transfer area to meet the requirement.

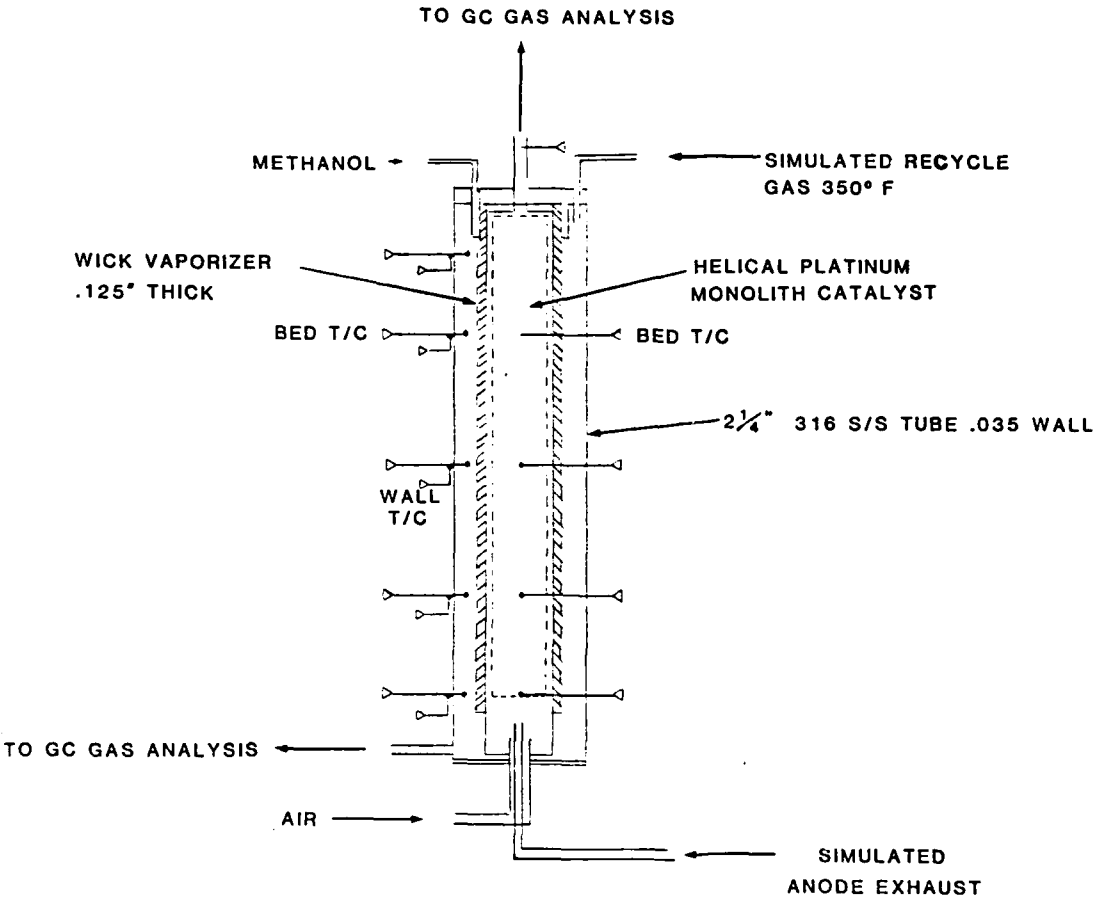

FIGURE 24.

CATALYTIC ANODE EXHAUST COMBUSTOR WITH VAPORIZER
5kW METHANOL FUEL PROCESSOR

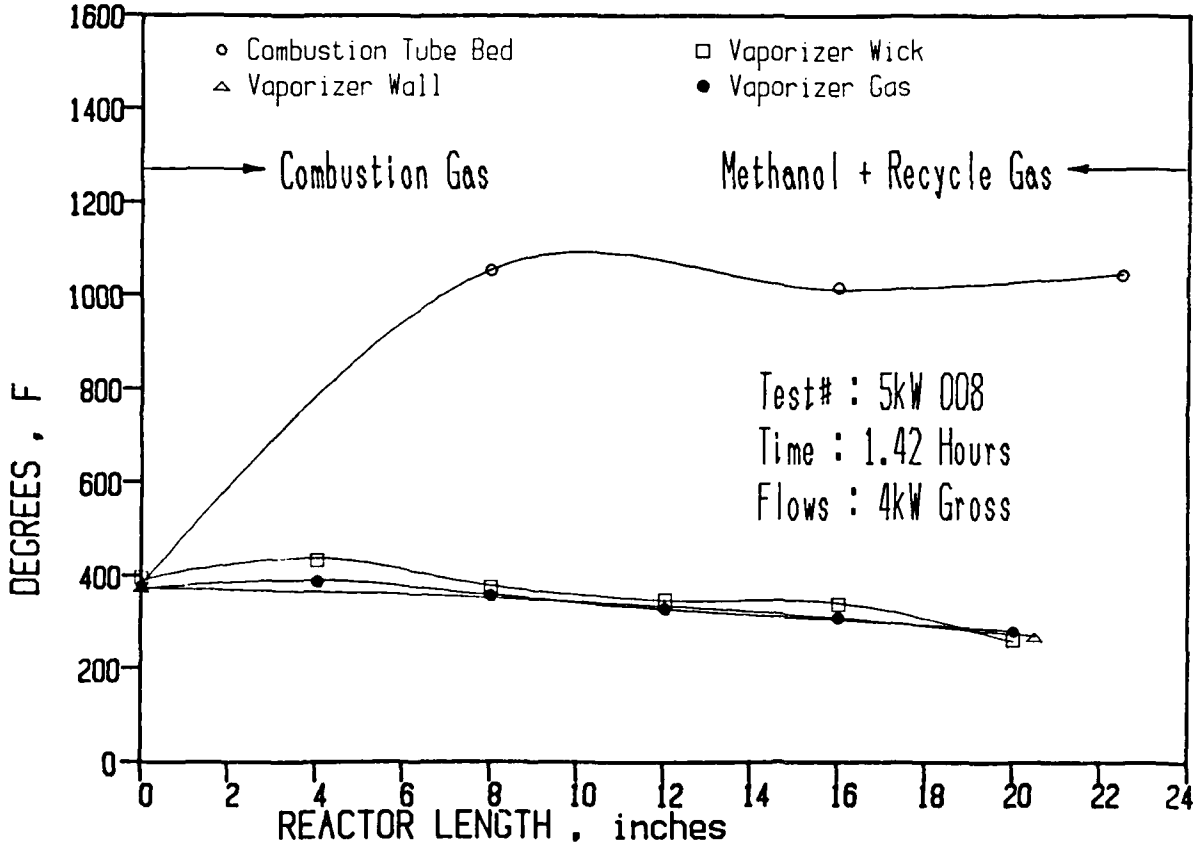

FIGURE 25.

VAPORIZER AND COMBUSTION TUBE TEMPERATURE PROFILE AT PART LOAD

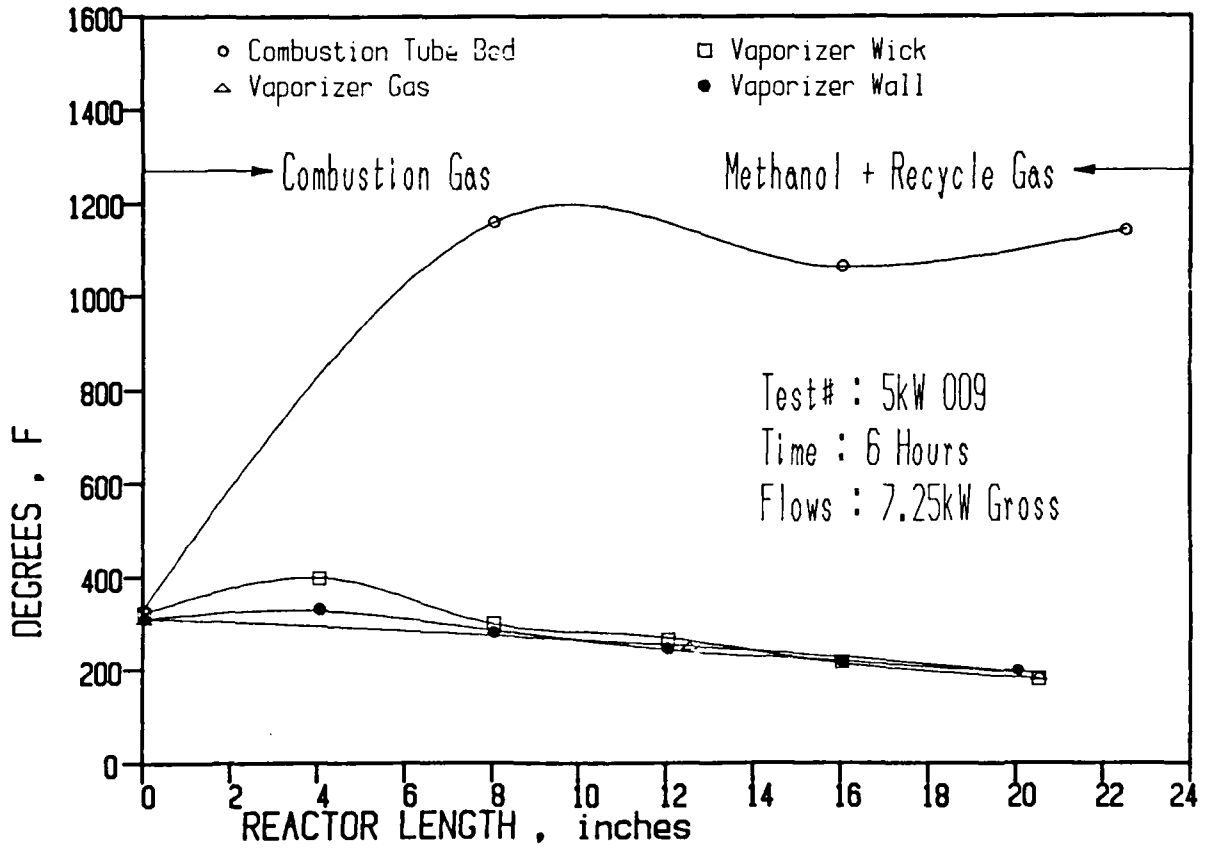

FIGURE 26.

VAPORIZER AND COMBUSTION TUBE TEMPERATURE PROFILE AT FULL LOAD

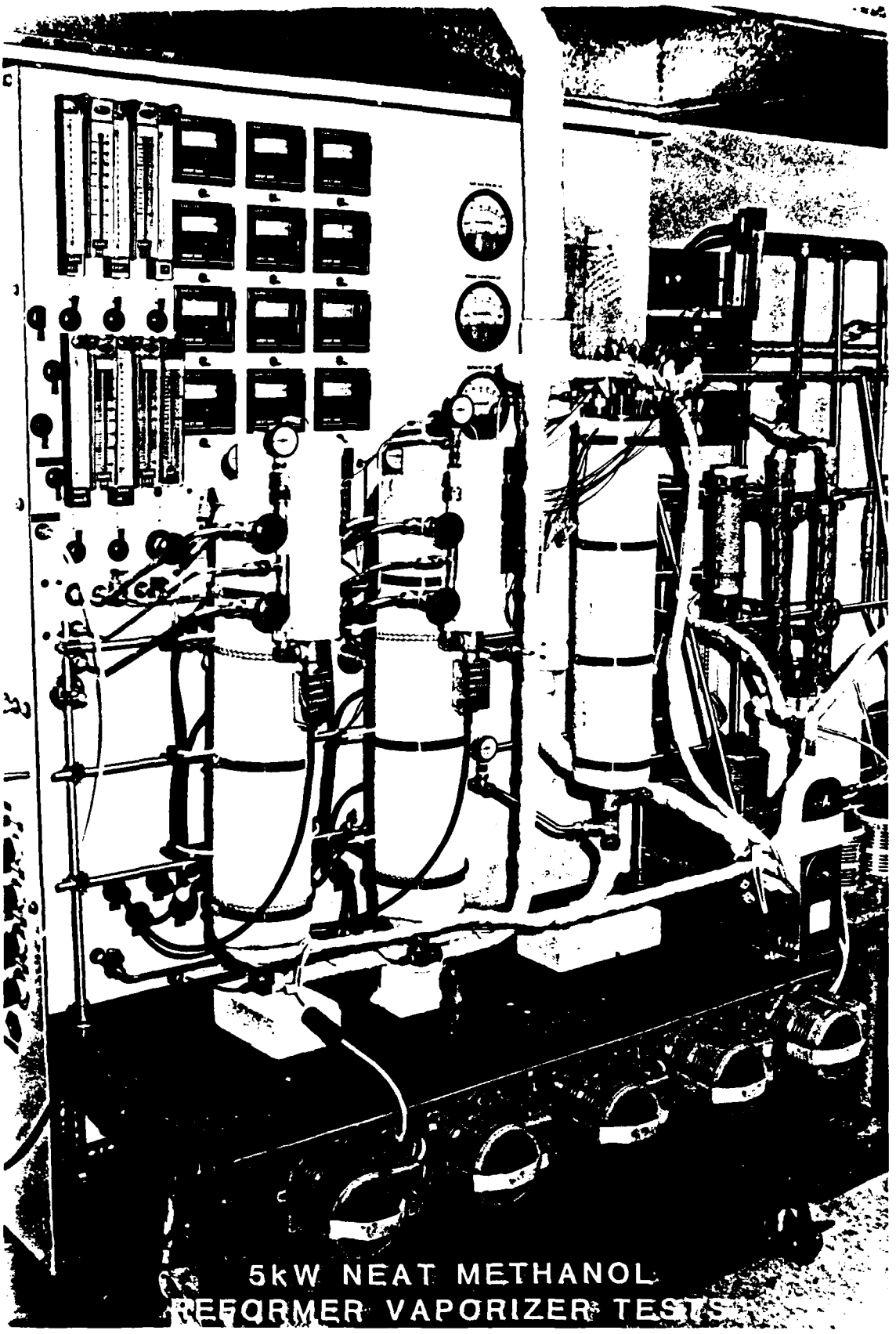

FIGURE 27.

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6.0 DESIGN AND CONSTRUCTION OF THE REFORMER

Based on the results obtained with the prelimnary design components, the reformer was redesigned as shown in Table 7. Pressure drop and heat transfer considerations used to arrive at this design are given in Appendices C and D, respectively.

A photograph of the key components are shown in Figure 28, and the assembled reformer can be seen in Figure 29. A cross-sectional drawing of the reformer is shown in Figure 30.

The overall weight of the reformer is 46 lbs. The weight breakdown is shown in Table 8.

TABLE 7.

5kW NEAT METHANOL REFORMER DESIGN PARAMETERS

ANNULAR REGION	INTERNAL COMBUSTION	VAPORIZER	REFORMER	EXTERNAL COMBUSTION I	EXTERNAL COMBUSTION II
Tube O.D. (inch)[1]	5.5 5.95	5.95 6.40	6.40 7.75	7.75 8.10	8.10 8.75
Wall (inch)	.025 .025	.025 .025	.025 .025	.025 .025	.025 .025
Tube I.D. (inch)[2]	5.45 5.90	5.90 6.35	6.35 7.70	7.70 8.05	8.05 8.70
Annulus (inch)	0.20	0.20	0.65	0.15	0.30
Cross Sectional Area (ft^2)	0.028	0.030	0.100	0.026	0.055
Surface Area [3] (ft^2)	3.12	3.12 3.35	3.35 4.06		
Surface Area [4] (ft^2)				3.04 3.18	3.18 3.44
Mass Flow					
4 kW ($lb/hr\ ft^2$)	2286	2141	531	2490	1170
7.25 kW ($lb/hr\ ft^2$)	2620	2454	582	2853	1341
Gas Velocity					
4 kW (ft/sec)	41	37	9.2	45	21
7.25 kW (ft/sec)	42	42	9.3	46	22
Heat Transfer h empty ($Btu/Hr\ ft^2\ ^oF$)	4.35	3.44	3.21	4.26	.2
Δp (inches of water)	0.2	0.2	4.0	0.24	0.03

1 Tube O.D. of inside and outside tube defining each annulus
2 Tube I.D. of inside and outside tube defining each annulus
3 Based on 2 ft high active area of internal annuli
4 Based on 1.5 ft high active area of combustion annuli I and II

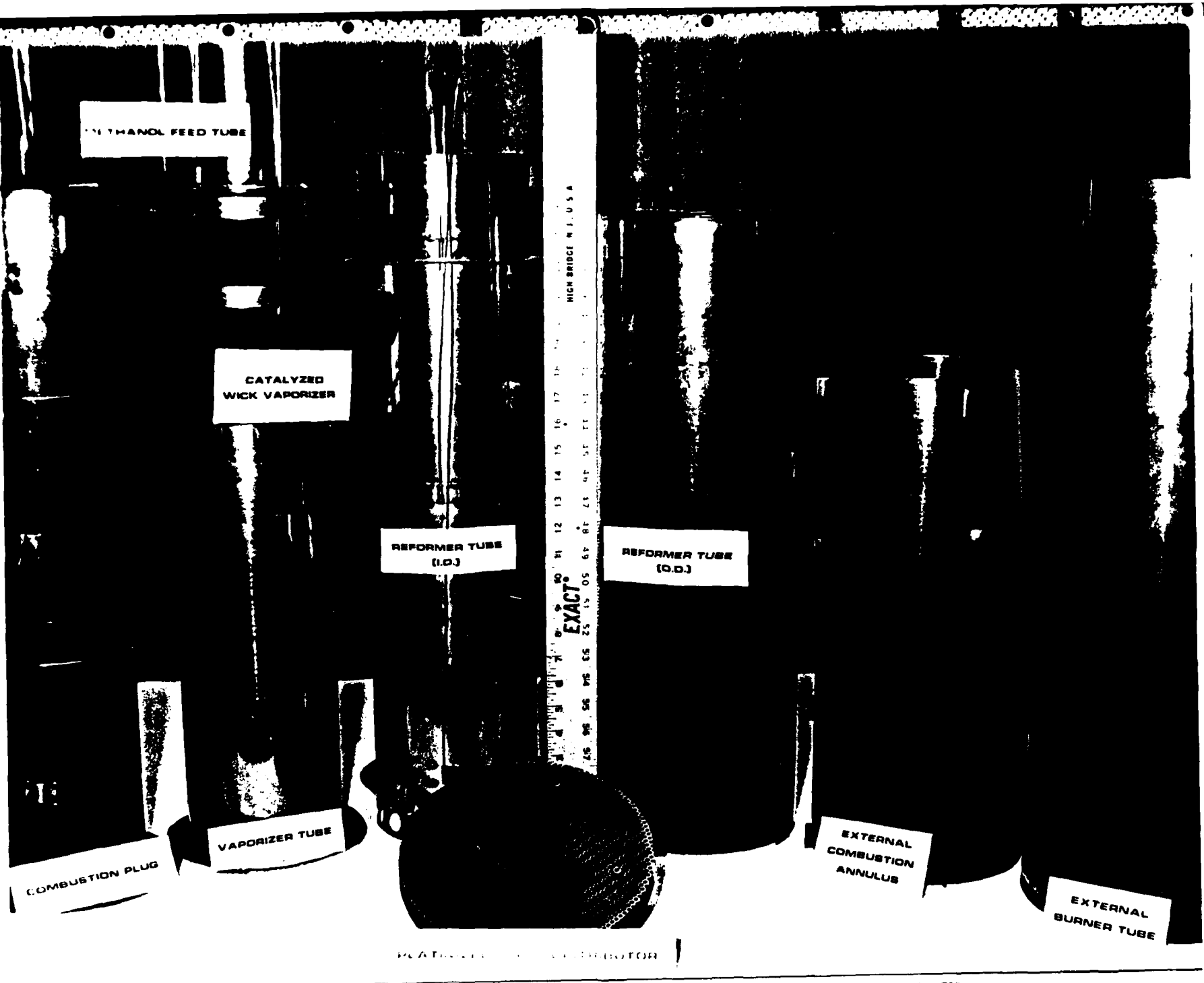

FIGURE 28. NEAT METHANOL REFORMER COMPONENTS - MODIFIED DESIGN

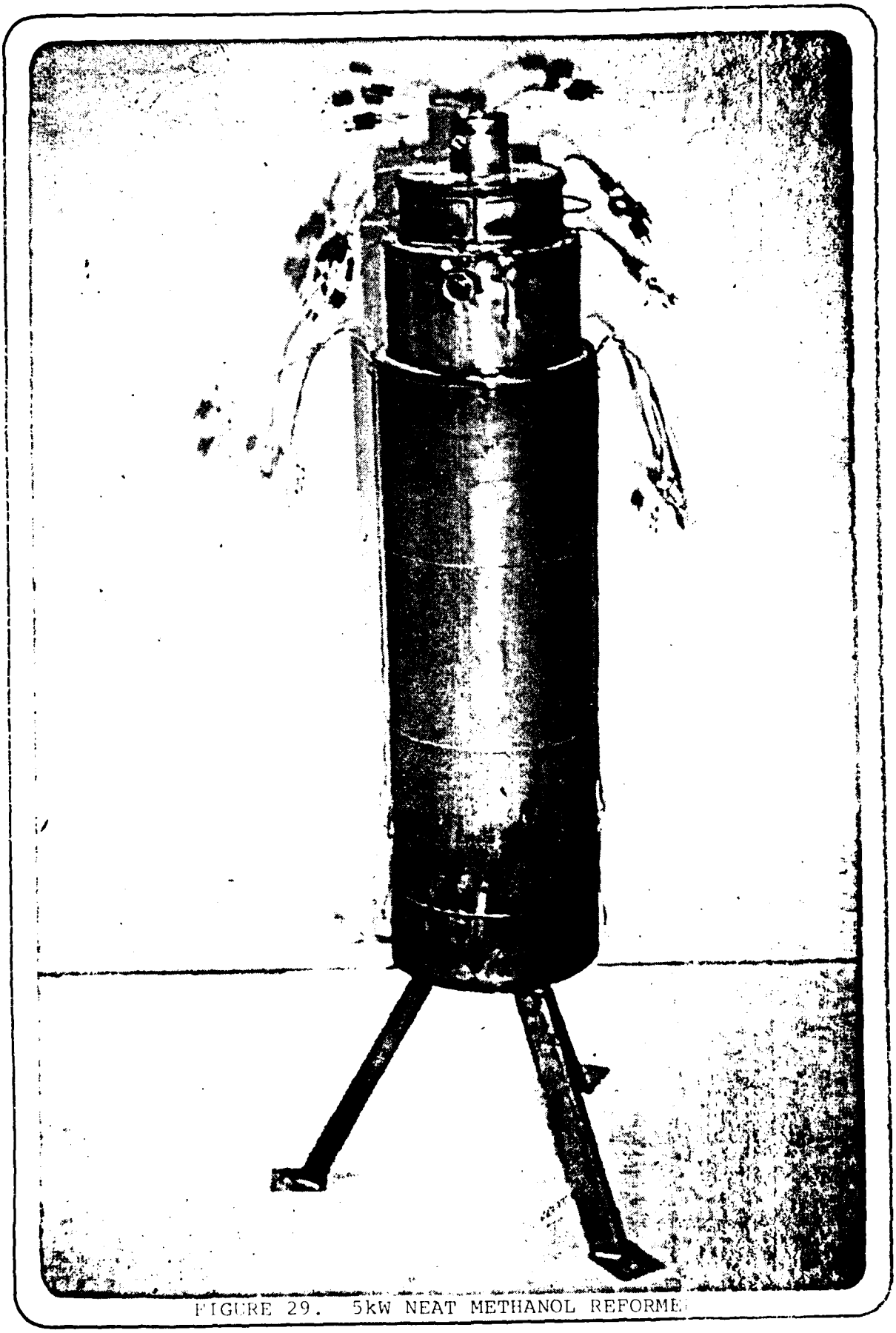

FIGURE 29. 5kW NEAT METHANOL REFORME

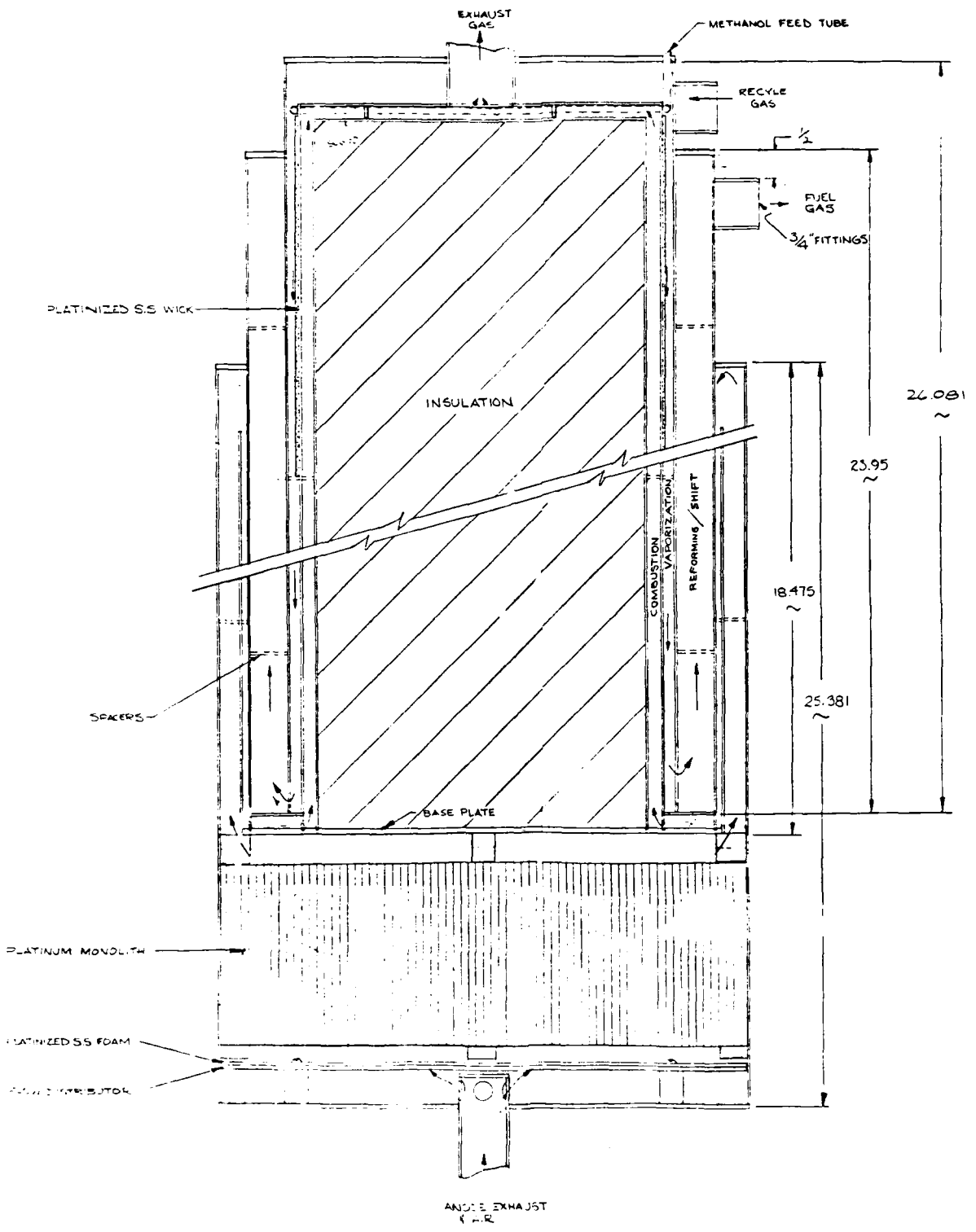

FIGURE 30.
5kW NEAT METHANOL REFORMER AS TESTED

TABLE 8
REFORMER WEIGHT BREAKDOWN

COMPONENT	WEIGHT, grams
Combustion Annulus (I) with Spacers	1,570
Vaporizer Cap	490
Reformer Upper Ring	40
Combustion Gas Flow Distributor and Combustor	470
Plug Assembly with Insulation	3,320
Combustion Tube	2,760
Reformer and Vaporizer Assembly	6,110
Catalyst	6,090
TOTAL	20,850 grams
	(45.93 lb)

The total weight does not include external insulation.

7.0 FUEL PROCESSOR TESTING

The objective of this series of tests was to verify performance of the reformer at full load (7.25 kW) and part load (4 kW) conditions, and to test startup and transient load operation.

Testing was carried out in the following sequence:

- Combustion of anode exhaust in catalytic burner - prior to complete assembly of reformer.
- Reforming at 7.25 kW flows with N_2 heat up.
- Reforming at 4 kW flows with N_2 heat up.
- Startup at 4 kW flow conditions.
- Startup at 4 kW flow conditions and transient to 7.25 kW flow conditions.

The flows used during these tests are summarized in Table 9, and Table 10 summarizes the tests conducted. A summary of the performance of the fuel processor is given in Table 11.

7.1 COMBUSTION OF ANODE EXHAUST

The combustion of simulated anode exhaust at idle (4 kW) and full load (7.25kW) conditions was tested prior to the installation of the catalyst bed and vaporizer sections of the reformer. The parameters tested included fuel flow rate and excess air rate. The reformer temperature profile is shown in Figure 31. The effect of excess combustion air can be seen in Table 12.

The tests indicated that adequate combustion was obtained. However, combustion at full load flows was better than at part load flows. Excess air tested was 2% to 10%. Unconverted hydrogen detected was 0.19% at part load and 0.1% at full load, inititally. Subsequent tests at full load resulted in unconverted H_2 of .03%. The unconverted hydrogen decreased with excess air and increasing (part load to full load) flows.

TABLE 9.
FLOWS USED IN REFORMER TESTING

COMPONENT	4 kW RATED FLOW		7.25 kW RATED FLOW	
	BURNER	VAPORIZER	BURNER	VAPORIZER
CH_3OH (CC/min)	-	41.61	-	78.02
H_2O (CC/min)	36.5	42.22	32.9	42.5
N_2 (SL/min)	156.5	155.4	147.7	142.16
H_2 (SL/min)	25.2	-	32.9	-
CO_2 (SL/min)	99.8	76.54	130.36	90.13
Air (SL/min)	62.6	-	78.3	-

TABLE 10.

SUMMARY OF TESTS CONDUCTED ON MODIFIED REFORMER DESIGN

TEST SUMMARIES	CONDITIONS	RESULTS
5kW 016	4 kW Flow Combustion	Uninsulated combustor yielded 850°F gas and 0.19% unburned H_2.
5kW 017	7.25 kW Flow Combustion	Uninsulated combustor yielded 962°F gas and 0.1% unburned H_2.
5kW 018	7.25 kW Flow Reforming. 10% Excess Combustion Air	87.7% conversion of methanol and 0.6% CO.
5kW 019	7.25 kW Flow Reforming. 10% Excess Combustion Air	99.2% Conversion of methanol and 1.06% CO after additional insulation.
5kW 020	7.25 kW Flow Reforming. 2-7% Excess Air.	Reducing combustion air to 2% excess air does not affect performance adversely. 99.85% conversion of MeOH exit CO at 1%.
5kW 021	7.25 kW gross flow. H_2O/CH_3OH = 1.3 stoichiometric air to burner.	Methanol flow distribution problem persists, methanol conversion 95.66% due to low temperature in one side of catalyst bed CO 0.67%.
5kW 022	7.25 kW gross flow. H_2O/CH_3OH = 1.1 0-2% excess combustion air simulated air preheat.	Preheating combustion air to 427°F increased combustion gas temp. 52°F, methanol conversion improved to 99.39%, CO higher at 1.46.
5kW 023	4kW gross flow design condition.	Low hydrogen level in exit gas indicates leak in system. Shutdown for repairs to fix leaks and poor methanol flow distribution.
5kW 024	4kW part load flows after methanol feed tube modification, and leak repair.	Improvement in temperature profile uniformity. Exit gas composition approximately as expected. MeOH conversion 91.1%.
5kW 025	4kW part load flows with simulated preheated (250°F) combustion air and additional insulation on top of reformer.	Preheating combustion air increases catalyst bed temperatures 55-65°F, and improves methanol conversion by 3.2% to 94.3%. Complete H_2 combustion in burner.
5kW 026	7.25 kW full load flow with simulated preheated (250°F) combustion air.	Improvement in temperature profile uniformity. MeOH conversion 83.8%, CO 0.8%.
5kW 027	Start-up at 4 kW methanol flow 30 SL/min air to vaporizer. 33 SL/min to combustion.	Start-up conditions reached within 30 minutes.
5kW 028	Start-up at 4 kW methanol flow, 40 SL/min air to vaporizer. 50 SL/min air to combustion.	Heat-up slower than test 5kW 026 with lower air flows.
5kW 029	Start-up at 4 kW methanol flow, 25 SL/min air to vaporizer. 33 SL/min air to combustion, switch to 4 kW normal flows.	Demonstrated start-up and switch to 4 kW flow conditions after 30 minutes 95.1% methanol conversion. CO 0.45%.
5kW 030	Start-up at 4kW methanol flow, 25 SL/min air to vaporizer. 33 SL/min air to combustion switch to 4 kW normal flows transient to 7.25 kW flow.	Transient to 7.25 flow conducted under simulated conditions. Catalyst bed inlet dropped 166°F initially and recovered. Methanol conversion 97%.

TABLE 11.

NEAT METHANOL REFORMER SPECIFICATIONS

	ACTUAL	REQUIRED	DESIRED
METHANOL FUEL CONSUMPTION:			
Rated Load (liter/hr)	4.68	7.75	4.0
50% Rated Load (liter/hr)	2.49	7.75	2.0
WEIGHT (Kg)	20.85	114	50
STARTUP TIME (min)	30	15	5
METHANOL FUEL QUALITY	OM 232	OM 232	Same but contaminated with up to 5% higher alcohols or hydrocarbons
QUALITY OF H_2 STREAM PRODUCED AT RATED LOAD:			
a. Carbon Monoxide (%)	0.8	Less Than 3%	Less Than 1%
b. Hydrogen (%)	26.9	At Least 25%	At Least 25%
QUALITY OF H_2 STREAM PRODUCED AT PART LOAD (4kw)			
a. Carbon Monoxide (%)	0.45	=	=
b. Hydrogen (%)	19.4	=	=

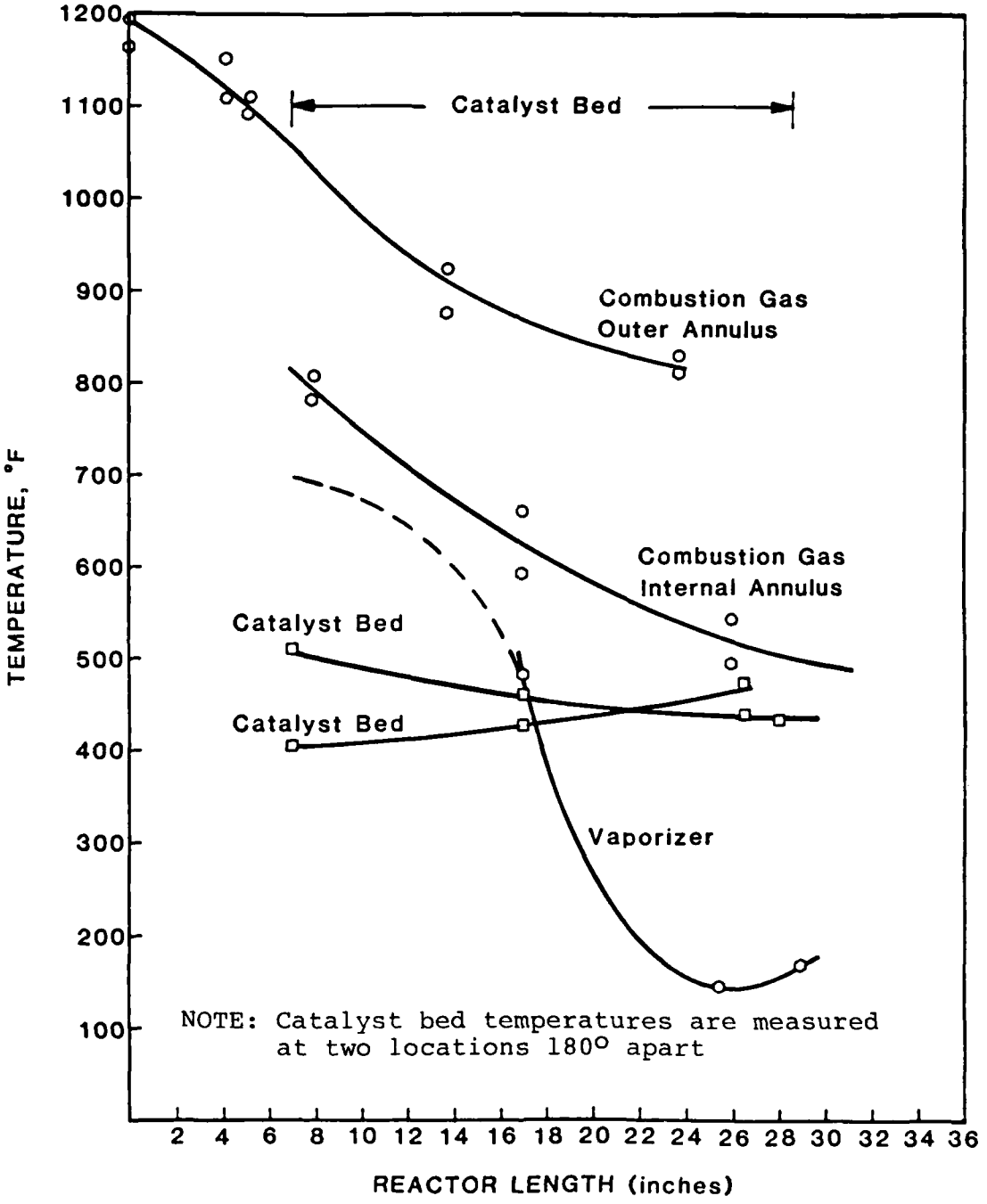

FIGURE 31.
REFORMER TEMPERATURE PROFILES

TABLE 12.

EFFECT OF EXCESS COMBUSTION AIR

TEST 5kW 020 7.25 kW Flow

AIR FLOW SL/MIN	% EXCESS	AVERAGE COMBUSTION TEMPERATURE ^{o}F	AVERAGE CATALYST BED TEMPERATURE ^{o}F	COMBUSTION EXHAUST H_2%	COMBUSTION EXHAUST O_2%	UNCONVERTED MeoH AT CATALYST BED EXIT
84	7%	1188	463	.02	0.80	.28%
82	5%	1189	466	.03	0.79	.15%
80	2%	1174	466	.03	0.75	.07%

NOTE

1. Water flow rate may have been higher than expected due to increase in temperature of water supply from D.I. water. This may have caused the decrease in unconverted methanol.

Testing with 250°F preheated air resulted in complete combustion of hydrogen. The CO level measured was 0.04% at full load. Reducing excess air to 2% did not have an adverse affect on the performance.

7.2 STEADY STATE TESTING

Initial testing of the fully assembled reformer was at 7.25 kW flows. After insulating the reformer, catalyst bed temperatures of 375-607°F were achieved and 99.85% methanol conversion was obtained. At these conditions, the CO level was 1%. In other tests where the catalyst bed exit temperature was lower, the CO level achieved was as low as 0.6%. Tests at H_2O/CH_3OH of 1.1 to 1.3 were conducted, and only small variations in performance were observed.

Plots of catalyst bed and vaporizer temperatures shown in Figure 32 indicated that flow distribution in the vaporizer and the catalyst bed were not uniform. This may be seen by the difference in temperatures measured at opposite sides of the reformer 180°F apart. This effect was attributed to nonuniform methanol fuel flow distribution, which was later corrected by the use of an improved liquid distribution manifold.

Figure 33 shows the temperature profiles after the modification. Here it can be seen that the vaporizer temperatures are much more uniform. The temperature dropped to a low of 135-145°F at 4 1/2 inches from the inlet of the vaporizer, and increased to 350-485°F at the exit.

Gas analysis at the exit of the vaporizer indicated that both methanol decomposition and reforming were occurring in the vaporizer. Hydrogen content of 1 - 5.24% was measured due to thermal and catalytic decomposition of methanol, and possibly some reforming of methanol over the platinum catalyst in the vaporizer. Conversion of methanol to hydrogen in the vaporizer is desirable since it spreads the thermal load over a larger area. In addition, the hydrogen maintains the inlet of the catalyst bed in a reduced state.

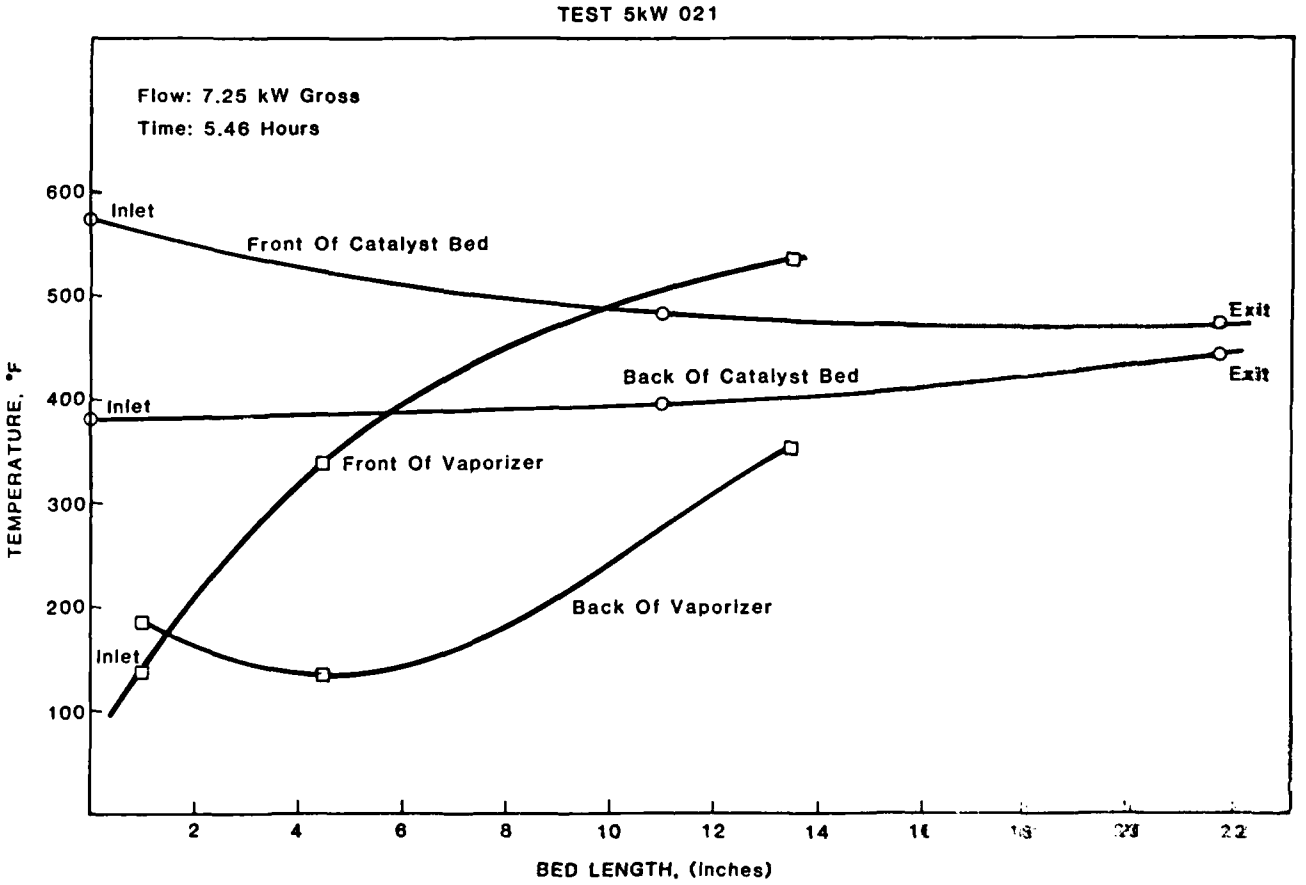

FIGURE 32.

VAPORIZER AND CATALYST BED TEMPERATURE PROFILE

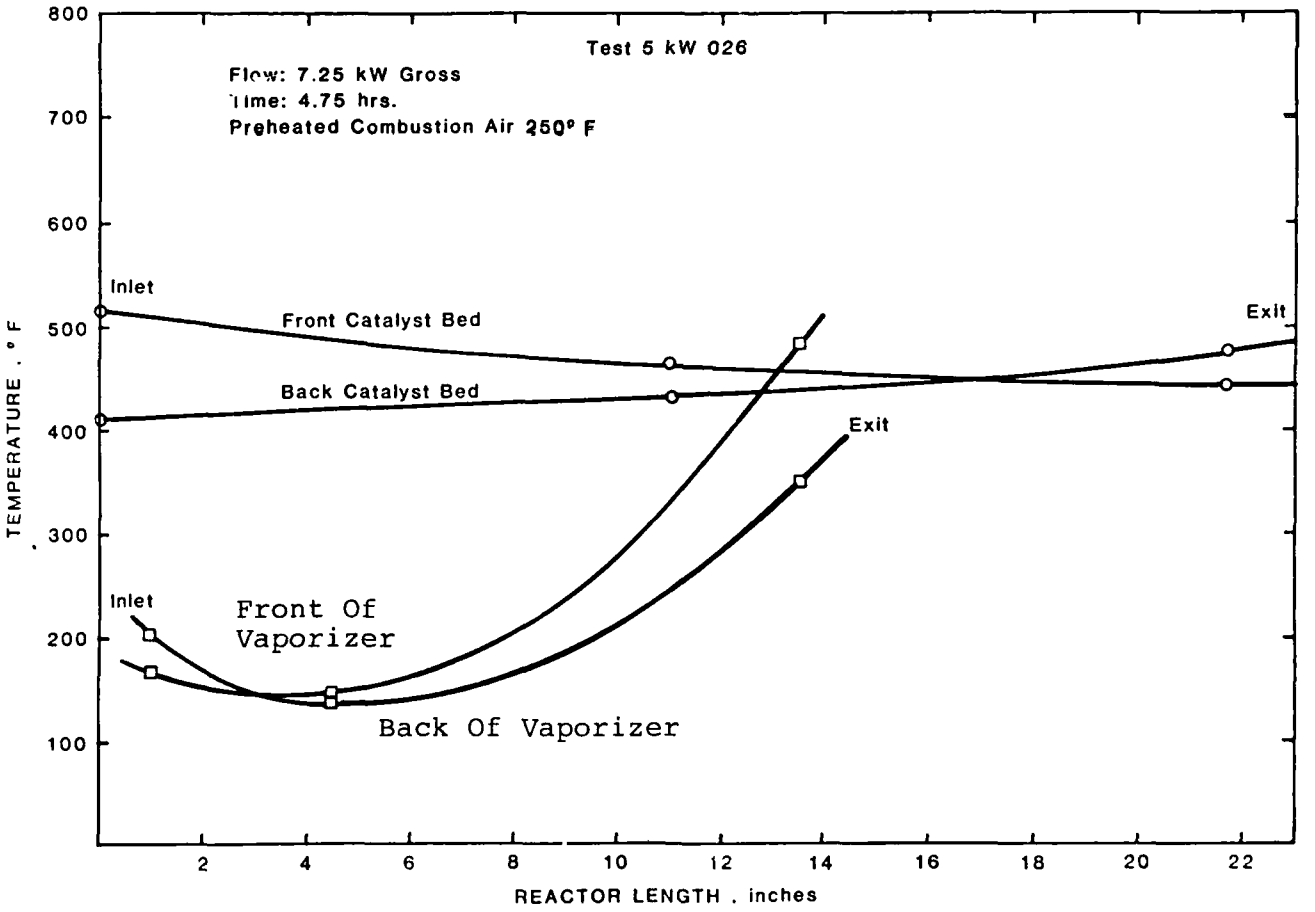

FIGURE 33.

VAPORIZER AND CATALYST BED TEMPERATURE PROFILE

Figure 31 depicts temperature profiles in the combustion annulus, catalyst bed and the vaporizer. The temperature gradients providing the driving force for heat transfer can be seen in this plot. The outer combustion gas annulus provides heat at approximately 1050°F to the catalyst bed inlet which is operating at 405-510°F, a gradient of 540-645°F. The combustion gas temperature drops rapidly and reaches approximately 950°F within 9 inches. This, essentially, is the reforming zone of the catalyst bed as determined by the large amount of heat absorbed by the reforming reaction. Further up the reformer the rate of heat loss from the outer combustion annulus is reduced as the exothermic shift reaction moves to completion. As the combustion gas moves up the internal annulus, it heats the vaporizer. In the vaporizer the gradient increases as the temperature of the incoming methanol drops near the top (inlet) of the vaporizer. This gradient causes a sharp increase in temperature after all of the methanol is vaporized. Preheating and vaporization of methanol is carried out by the exiting combustion gas, which is at its lowest temperature (490°F) as it leaves the reformer. Analysis of the combustion exit gas during test 5kW 025 indicated complete hydrogen combustion, and no CO was detected in the reformer exhaust stream.

7.3 START-UP AND TRANSIENTS

During start-up, the reformer operates on methanol and air only. Start-up was tested by introducing the 4 kW methanol flow and air into the vaporizer section of the reformer to partially oxidize the methanol, providing heat for vaporization and heating of the reformer to its operating temperature. The gas leaving the catalyst bed was diverted to the reformer burner where it was combusted with air.

Results of this testing indicated that the platinized wick was not effective for oxidizing methanol and raising the temperature in the vaporizer. Instead, an exothermic reaction was

observed at the inlet of the catalyst bed as depicted in the temperature profile of Figure 34. This was interpreted as oxidation of the catalyst and thermal and/or catalytic decomposition of methanol. This process resulted in a heat-up of the reformer to operating conditions after 30 minutes.

Analysis of the gas leaving the catalyst bed during start-up conditions indicated methanol conversion up to 95.1% with hydrogen measured at 19.2 - 33%. CO was at 0.45 - 2.39%, and methanol at 0.3 - 1.23%. During the start-up mode, this gas was fed to the burner where it was combusted with air to provide additional heat for start-up.

Figure 35 depicts the temperature profile in the vaporizer and catalyst bed seven minutes and 4.6 hours after switching from start-up conditions to 4 kW flow conditions with simulated anode recycle combustion gas. The data indicates that even after switching to normal operating conditions, there is still a slight increase in temperature as the reformer operates at 4 kW flows. This indicates that higher start-up temperatures may be desired.

A transient test was conducted by increasing the flows to 7.25 kW from 4 kW. Figure 36 depicts catalyst bed temperatures at 4 kW and 7.25 kW conditions. A drop in catalyst bed temperatures of 166°F (average) was recorded, followed by a temperature recovery. However, after 42 minutes the catalyst inlet temperatures were still an average of 155°F lower with 7.25 kW flows as compared to the 4 kW flow conditions. Overall methanol conversion at 7.25 kW flow condition was 97% with CO at 1.12%. Transients under these conditions result in unconverted methanol levels increasing after the transient, and gradually decreasing to the normal level with time.

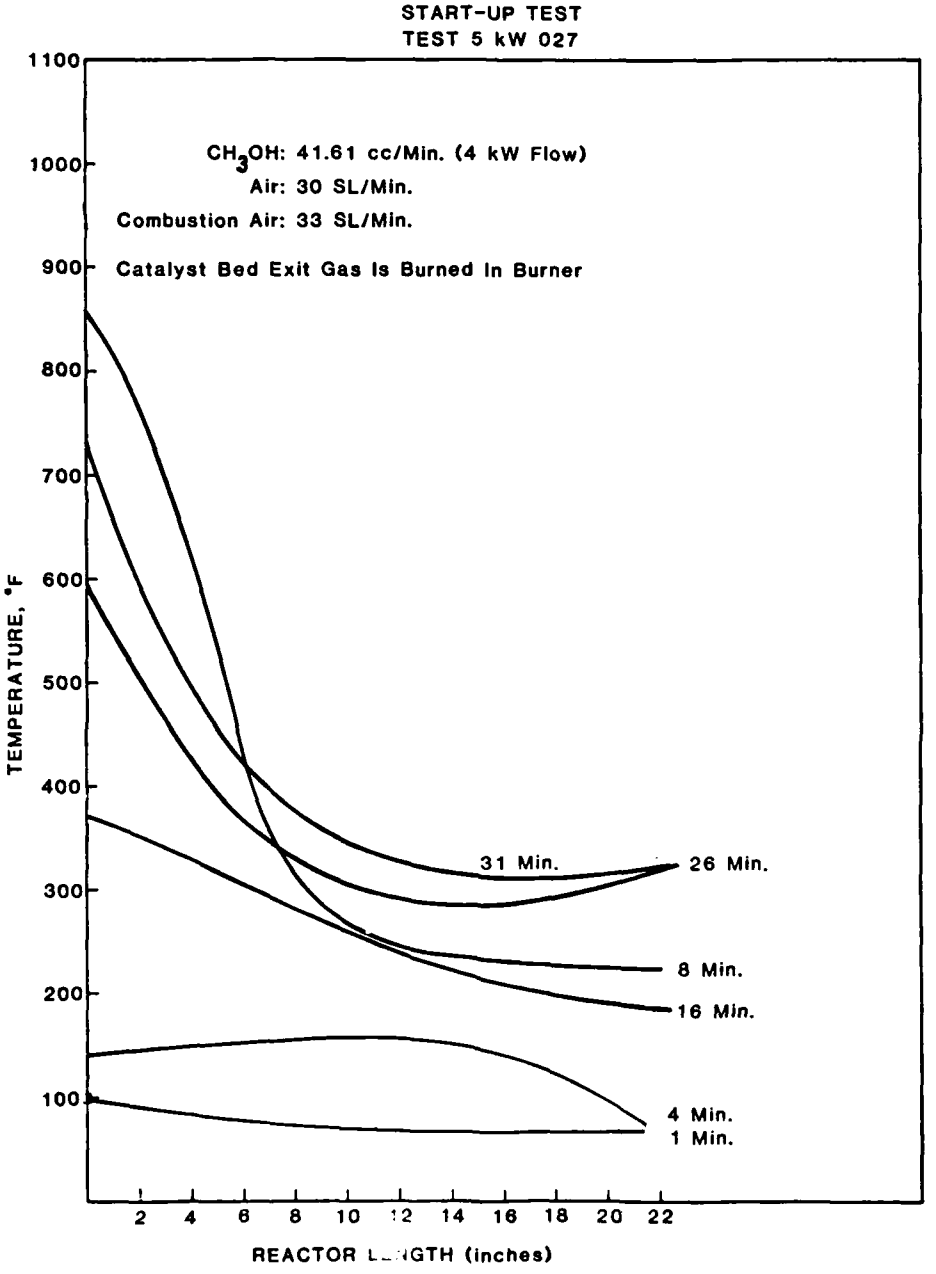

FIGURE 34.
START-UP - CATALYST BED TEMPERATURE PROFILE

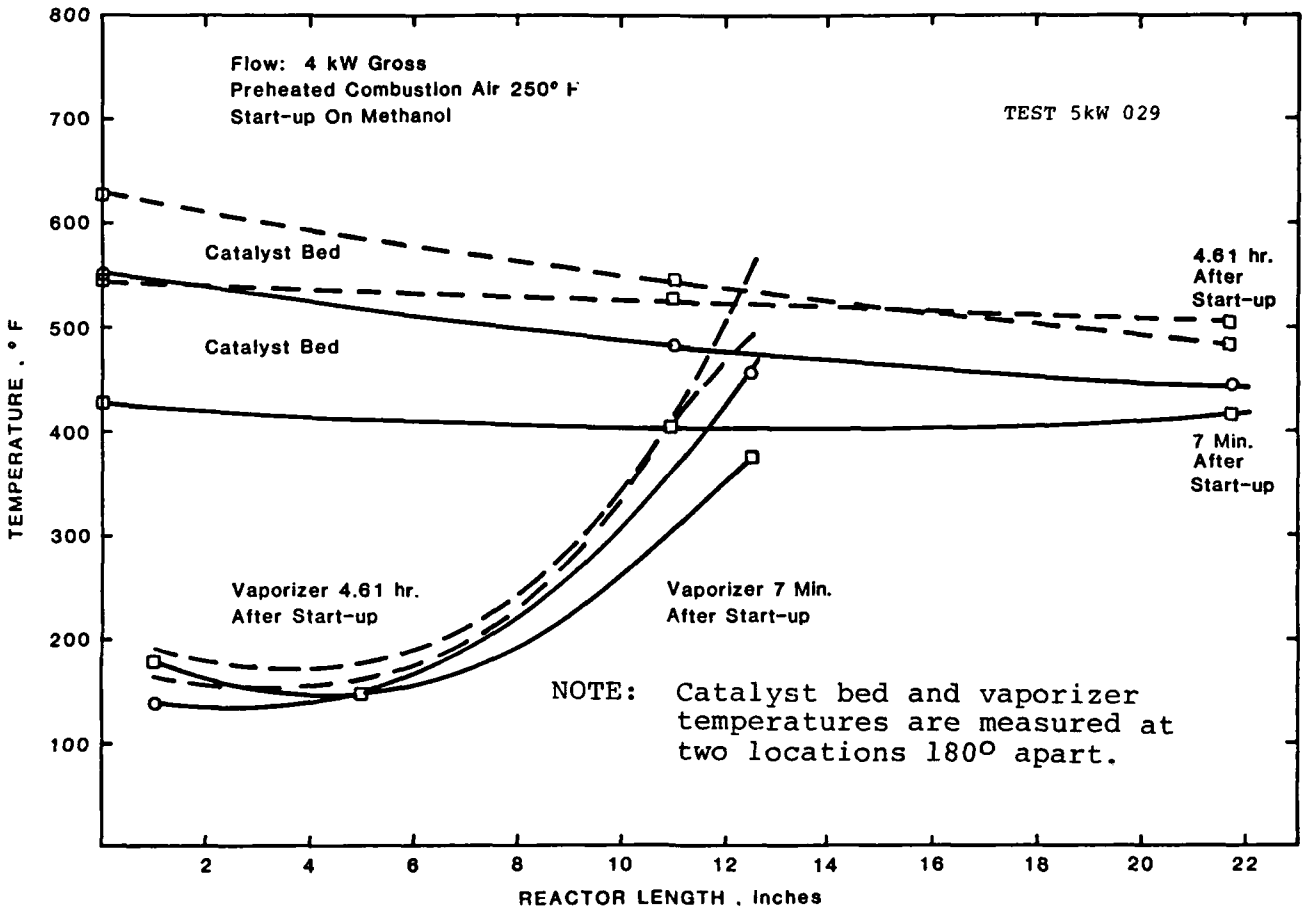

FIGURE 35.

VAPORIZER AND CATALYST BED
TEMPERATURE PROFILE AFTER START-UP

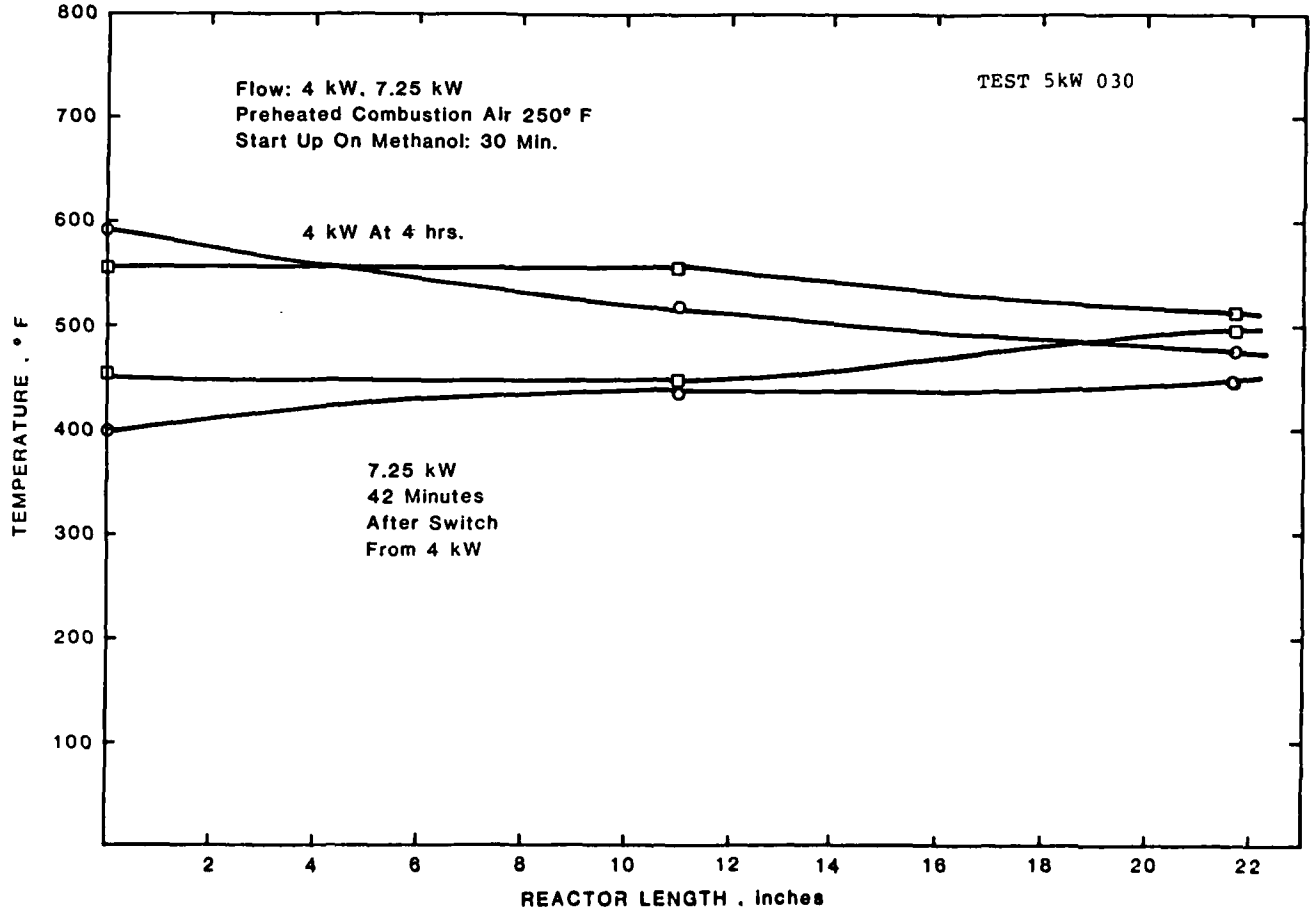

FIGURE 36.

CATALYST BED TEMPERATURE PROFILE BEFORE AND AFTER TRANSIENT

8.0 CONCLUSIONS AND RECOMMENDATIONS

A preliminary conceptual design of a neat methanol reformer utilizing burner exhaust as the source of water was developed. A reformer having sufficient capacity for a 5kW fuel cell power unit was built and tested.

The reformer weight is less than half of the permissible weight. This allows for additional weight of a recycle blower and recycle gas heat exchanger. Fuel consumption is also less than the maximum allowable figure.

Start-up time based on limited testing was found to be longer than required. Thirty minutes were needed in tests conducted, whereas 15 minutes is required and 5 minutes desired. The developmental design incorporates design changes that are intended to improve the start-up time, and are shown in Figure 37. The changes include:

- longer platinized wick;
- coverage of gas passage holes between vaporizer and reformer with platinized wick;
- replacement of monolith catalyst with additional layer of platinized wick in the burner.

The quality of hydrogen exceeds the requirement of 25% at rated load and the CO level is better than the desired level of 1%. At part load the hydrogen drops to 19.4% and the CO is 0.45%.

All the required objectives for the reformer were met with the exception of startup time. The desired objectives were met or exceeded for weight and quality of hydrogen steam. The fuel consumption could meet the desired level if lower parasitic power requirements were assumed. A very conservative parasitic power requirement was assumed in the basis for the reformer design, requiring a large portion of the fuel flow to generate parasitic power. If parasitic losses can be reduced, overall fuel consumption can be reduced.

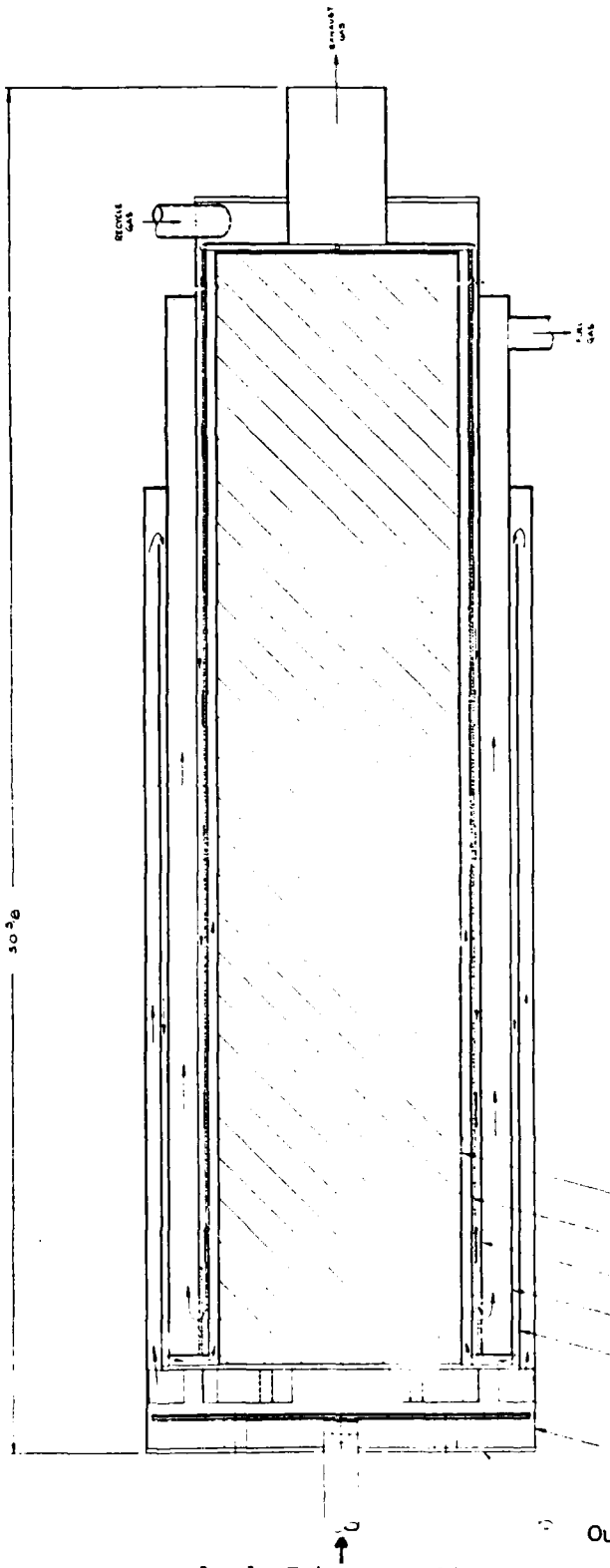

FIGURE 37.

5kW NEAT METHANOL REFORMER DEVELOPMENT DESIGN

Recommendations for future development of this technology are as follows:

- Testing of developmental design with final modifications is suggested.
- Additional testing of start-up and transient conditions is required.
- Incorporate the recycle blower and test reformer in conjunction with a fuel cell power unit.
- Consider second generation design with enhanced heat transfer (i.e. finned surfaces and other heat transfer enhancement) in order to reduce size of the reformer.
- Consider lighter weight materials where possible in order to reduce weight.

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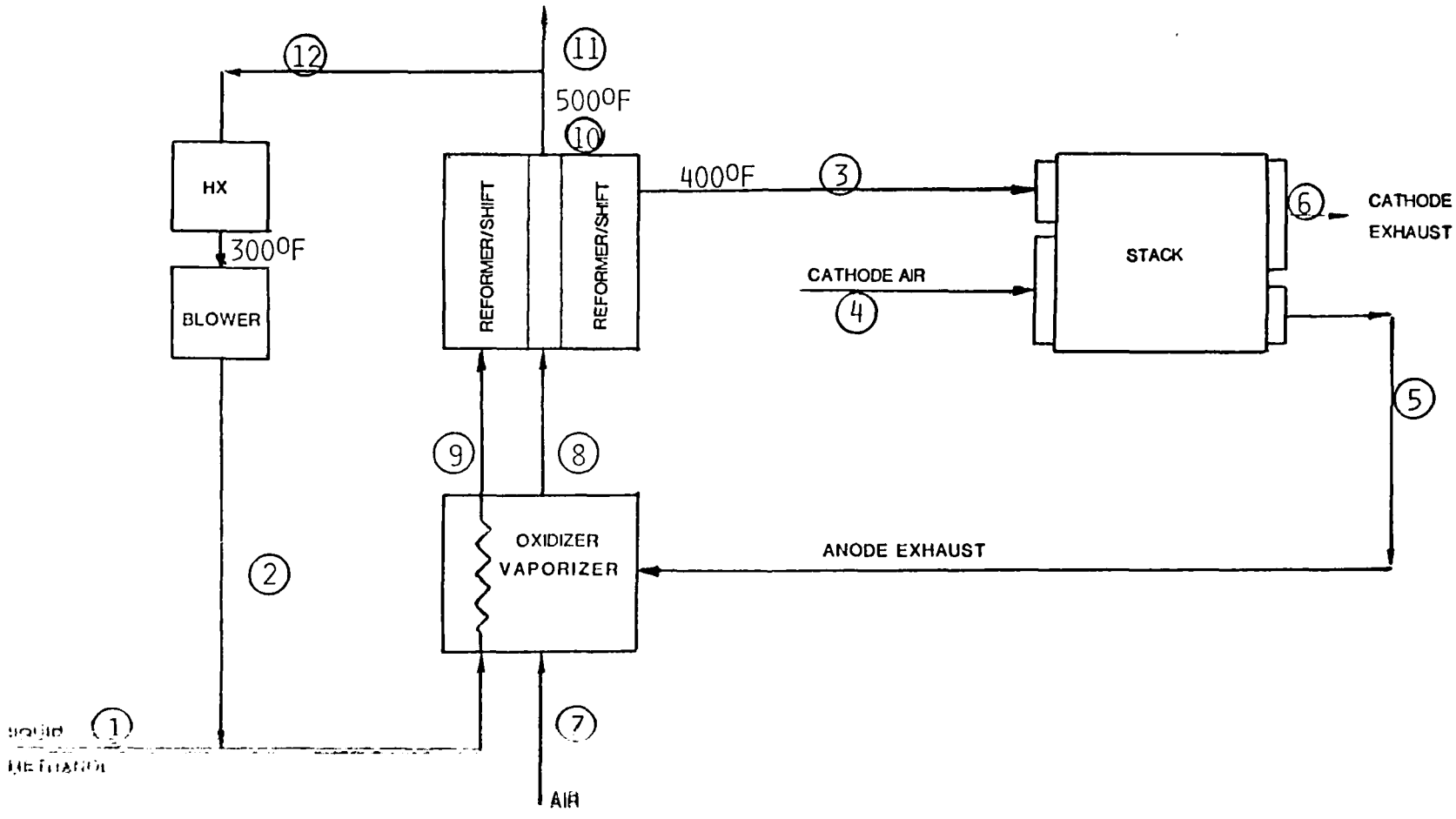
APPENDIX A

NODE ARRAY ANALYSIS - MATERIAL AND ENERGY BALANCES

CONFIGURATION #4



5kW NEAT METHANOL FUEL PROCESSOR SYSTEM

ENERGY RESEARCH CORP.

DATE: 12-13-1984

NODE ARRAY ANALYSIS

CONFIGURATION #4

FLOW RATE - lb mole/hr

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	TOTAL	Press ATM	Temp Deg-F	Enthalpy BTU/hr	NODE
1	0.000	0.000	0.000	0.000	0.000	0.000	0.255	0.255	1.000	60	-2.3924E+04	1
2	0.000	0.312	0.000	0.504	0.000	0.795	0.000	1.611	1.000	300	-1.0805E+05	2
3	0.736	0.087	0.031	0.729	0.000	0.795	0.000	2.377	1.000	400	-1.1855E+05	3
4	0.000	0.023	0.000	0.000	0.552	2.076	0.000	2.651	1.000	250	1.0728E+04	4
5	0.184	0.281	0.031	0.729	0.000	0.795	0.000	2.020	1.000	350	-1.4131E+05	5
6	0.000	0.380	0.000	0.000	0.276	2.076	0.000	2.732	1.000	350	-2.3379E+04	6
7	0.000	0.004	0.000	0.000	0.107	0.403	0.000	0.515	1.000	70	1.4380E+03	7
8	0.000	0.470	0.000	0.759	0.000	1.199	0.000	2.428	1.000	812	-1.5209E+05	8
9	0.000	0.312	0.000	0.504	0.000	0.795	0.255	1.866	1.000	712	-1.1975E+05	9
10	0.000	0.470	0.000	0.759	0.000	1.199	0.000	2.428	1.000	500	-1.5877E+05	10
11	0.000	0.158	0.000	0.255	0.000	0.403	0.000	0.817	1.000	500	-5.3420E+04	11
12	0.000	0.312	0.000	0.504	0.000	0.795	0.000	1.611	1.000	500	-1.0535E+05	12

COMPOSITION - MOLE PERCENT

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	NODE
1	0.0	0.0	0.0	0.0	0.0	0.0	100.0	1
2	0.0	19.3	0.0	31.3	0.0	49.4	0.0	2
3	31.0	3.6	1.3	30.7	0.0	33.5	0.0	3
4	0.0	0.9	0.0	0.0	20.8	78.3	0.0	4
5	9.1	13.9	1.5	36.1	0.0	39.4	0.0	5
6	0.0	13.9	0.0	0.0	10.1	76.0	0.0	6
7	0.0	0.9	0.0	0.0	20.8	78.3	0.0	7
8	0.0	19.3	0.0	31.3	0.0	49.4	0.0	8
9	0.0	16.7	0.0	27.0	0.0	42.6	13.7	9
10	0.0	19.3	0.0	31.3	0.0	49.4	0.0	10
11	0.0	19.3	0.0	31.3	0.0	49.4	0.0	11
12	0.0	19.3	0.0	31.3	0.0	49.4	0.0	12

INPUT PARAMETERS:

NUMBER OF CELLS	79
CELL AREA , cm2	1070.0
GROSS POWER , kW	7.25
PARASITIC POWER CONSUMPTION , kW	2.25
ANODE UTILIZATION	0.75
CATHODE UTILIZATION	0.50
H2O/Methanol AT REFORMER INLET	1.22
EXCESS OXYGEN AT BURNER INLET	0.0%

OUTPUT PARAMETERS:

CELL VOLTAGE , mV	540.2
CURRENT DENSITY , mA/cm2	159.8
NET EFFICIENCY (LHV)	24.3%
STACK HEAT LOAD , BTU/hr	32119.1
REFORMER HEAT LOAD , BTU/hr	5479.1
HEAT EX. HEAT LOAD , BTU/hr	2700.4
BLOWER FLOW RATE , cu. ft/hr	893.9

MATERIAL & ENERGY BALANCE - FULL LOAD DESIGN CONDITION

ENERGY RESEARCH CORP.

DATE: 12-14-1984

NODE ARRAY ANALYSIS

CONFIGURATION #4

FLOW RATE - lb mole/hr

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	TOTAL	Press ATM	Temp Deg-F	Enthalpy BTU/hr	NODE
1	0.000	0.000	0.000	0.000	0.000	0.000	0.136	0.136	1.000	60	-1.2741E+04	1
2	0.000	0.310	0.000	0.428	0.000	0.869	0.000	1.607	1.000	300	-9.5178E+04	2
3	0.402	0.180	0.006	0.558	0.000	0.869	0.000	2.015	1.000	400	-1.0035E+05	3
4	0.000	0.011	0.000	0.000	0.261	0.983	0.000	1.255	1.000	250	5.0795E+03	4
5	0.141	0.265	0.006	0.558	0.000	0.869	0.000	1.839	1.000	350	-1.1077E+05	5
6	0.000	0.187	0.000	0.000	0.131	0.983	0.000	1.301	1.000	350	-1.1780E+04	6
7	0.000	0.003	0.000	0.000	0.073	0.276	0.000	0.353	1.000	70	9.8453E+02	7
8	0.000	0.409	0.000	0.564	0.000	1.145	0.000	2.118	1.000	738	-1.1762E+05	8
9	0.000	0.310	0.000	0.428	0.000	0.869	0.136	1.743	1.000	638	-1.0008E+05	9
10	0.000	0.409	0.000	0.564	0.000	1.145	0.000	2.118	1.000	500	-1.2194E+05	10
11	0.000	0.099	0.000	0.136	0.000	0.276	0.000	0.511	1.000	500	-2.9409E+04	11
12	0.000	0.310	0.000	0.428	0.000	0.869	0.000	1.607	1.000	500	-9.2535E+04	12

COMPOSITION - MOLE PERCENT

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	NODE
1	0.0	0.0	0.0	0.0	0.0	0.0	100.0	1
2	0.0	19.3	0.0	26.6	0.0	54.1	0.0	2
3	19.9	8.9	0.3	27.7	0.0	43.1	0.0	3
4	0.0	0.9	0.0	0.0	20.8	78.3	0.0	4
5	7.7	14.4	0.3	30.3	0.0	47.3	0.0	5
6	0.0	14.4	0.0	0.0	10.0	75.5	0.0	6
7	0.0	0.9	0.0	0.0	20.8	78.3	0.0	7
8	0.0	19.3	0.0	26.6	0.0	54.1	0.0	8
9	0.0	17.8	0.0	24.6	0.0	49.8	7.8	9
10	0.0	19.3	0.0	26.6	0.0	54.1	0.0	10
11	0.0	19.3	0.0	26.6	0.0	54.1	0.0	11
12	0.0	19.3	0.0	26.6	0.0	54.1	0.0	12

INPUT PARAMETERS:

NUMBER OF CELLS	79
CELL AREA , cm2	1070.0
GROSS POWER , kW	4.00
PARASITIC POWER CONSUMPTION , kW	1.24
ANODE UTILIZATION	0.65
CATHODE UTILIZATION	0.50
H2O/Methanol AT REFORMER INLET	2.28
EXCESS OXYGEN AT BURNER INLET	0.0%

OUTPUT PARAMETERS:

CELL VOLTAGE , mV	629.6
CURRENT DENSITY , mA/cm2	75.2
NET EFFICIENCY (LHV)	25.2%
STACK HEAT LOAD , BTU/hr	13626.1
REFORMER HEAT LOAD , BTU/hr	4589.8
HEAT EX. HEAT LOAD , BTU/hr	2643.0
BLOWER FLOW RATE , cu. ft/hr	891.8

MATERIAL AND ENERGY BALANCE - PART LOAD DESIGN CONDITION

ENERGY RESEARCH CORP.

DATE: 12-13-1994

NODE ARRAY ANALYSIS

CONFIGURATION #4

FLOW RATE - lb mole/hr

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	TOTAL	Press ATM	Temp Deg-F	Enthalpy BTU/hr	NODE
1	0.000	0.000	0.000	0.000	0.000	0.000	0.245	0.245	1.000	60	-2.2916E+04	1
2	0.000	0.269	0.000	0.505	0.000	0.689	0.000	1.463	1.000	300	-1.0466E+05	2
3	0.695	0.063	0.039	0.711	0.000	0.689	0.000	2.197	1.000	400	-1.1461E+05	3
4	0.000	0.023	0.000	0.000	0.556	2.093	0.000	2.672	1.000	250	1.0815E+04	4
5	0.139	0.257	0.039	0.711	0.000	0.689	0.000	1.835	1.000	350	-1.3725E+05	5
6	0.000	0.386	0.000	0.000	0.278	2.093	0.000	2.757	1.000	350	-2.3796E+04	6
7	0.000	0.004	0.000	0.000	0.089	0.334	0.000	0.427	1.000	70	1.1917E+03	7
8	0.000	0.400	0.000	0.749	0.000	1.024	0.000	2.173	1.000	761	-1.4667E+05	8
9	0.000	0.269	0.000	0.505	0.000	0.689	0.245	1.708	1.000	661	-1.1697E+05	9
10	0.000	0.400	0.000	0.749	0.000	1.024	0.000	2.173	1.000	500	-1.5171E+05	10
11	0.000	0.130	0.000	0.245	0.000	0.334	0.000	0.709	1.000	500	-4.9533E+04	11
12	0.000	0.269	0.000	0.505	0.000	0.689	0.000	1.463	1.000	500	-1.0218E+05	12

COMPOSITION - MOLE PERCENT

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	NODE
1	0.0	0.0	0.0	0.0	0.0	0.0	100.0	1
2	0.0	18.4	0.0	34.5	0.0	47.1	0.0	2
3	31.6	2.9	1.8	32.3	0.0	31.4	0.0	3
4	0.0	0.9	0.0	0.0	20.8	78.3	0.0	4
5	7.6	14.0	2.1	38.7	0.0	37.6	0.0	5
6	0.0	14.0	0.0	0.0	10.1	75.9	0.0	6
7	0.0	0.9	0.0	0.0	20.8	78.3	0.0	7
8	0.0	18.4	0.0	34.5	0.0	47.1	0.0	8
9	0.0	15.8	0.0	29.6	0.0	40.4	14.3	9
10	0.0	18.4	0.0	34.5	0.0	47.1	0.0	10
11	0.0	18.4	0.0	34.5	0.0	47.1	0.0	11
12	0.0	18.4	0.0	34.5	0.0	47.1	0.0	12

INPUT PARAMETERS:

NUMBER OF CELLS	79
CELL AREA , cm2	1070.0
GROSS POWER , kW	7.25
PARASITIC POWER CONSUMPTION , kW	2.25
ANODE UTILIZATION	0.80
CATHODE UTILIZATION	0.50
H2O/Methanol AT REFORMER INLET	1.10
EXCESS OXYGEN AT BURNER INLET	0.0%

OUTPUT PARAMETERS:

CELL VOLTAGE , mV	535.8
CURRENT DENSITY , mA/cm2	160.0
NET EFFICIENCY (LHV)	25.4%
STACK HEAT LOAD , BTU/hr	32506.7
REFORMER HEAT LOAD , BTU/hr	2691.8
HEAT EX. HEAT LOAD , BTU/hr	2481.8
BLOWER FLOW RATE , cu. ft/hr	812.1

MATERIAL AND ENERGY BALANCE
FULL LOAD AT H_2O/C = 1.1 and 80% ANODE UTILIZATION

ENERGY RESEARCH CORP.

DATE: 12-07-1988

NODE ARRAY ANALYSIS

CONFIGURATION #4

FLOW RATE - lb mole/hr

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	TOTAL	Press ATM	Temp Deg-F	Enthalpy BTU/hr	NODE
1	0.000	0.000	0.000	0.000	0.000	0.000	0.257	0.257	[illegible]	60	-2.[illegible]E+04	1
2	0.000	0.283	0.000	0.445	0.000	0.719	0.000	1.447	[illegible]	300	-9.[illegible]E+04	2
3	0.735	0.064	0.038	0.664	0.000	0.719	0.000	2.220	[illegible]	400	-1.[illegible]E+05	3
4	0.000	0.023	0.000	0.000	0.551	2.072	0.000	2.646	[illegible]	250	1.07[illegible]E+04	4
5	0.184	0.259	0.038	0.664	0.000	0.719	0.000	1.864	[illegible]	350	-1.29[illegible]E+05	5
6	0.000	0.379	0.000	0.000	0.275	2.072	0.000	2.726	[illegible]	350	-2.32[illegible]E+04	6
7	0.000	0.005	0.000	0.000	0.111	0.417	0.000	0.532	[illegible]	70	1.48[illegible]E+03	7
8	0.000	0.447	0.000	0.702	0.000	1.136	0.000	2.285	[illegible]	863	-1.40[illegible]E+05	8
9	0.000	0.283	0.000	0.445	0.000	0.719	0.257	1.705	[illegible]	763	-1.07[illegible]E+05	9
10	0.000	0.447	0.000	0.702	0.000	1.136	0.000	2.285	[illegible]	300	-1.47[illegible]E+05	10
11	0.000	0.164	0.000	0.257	0.000	0.417	0.000	0.838	[illegible]	500	-5.42[illegible]E+04	11
12	0.000	0.283	0.000	0.445	0.000	0.719	0.000	1.447	[illegible]	509	-9.[illegible]E+04	12

COMPOSITION - MOLE PERCENT

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	NODE
1	0.0	0.0	0.0	0.0	0.0	0.0	100.0	1
2	0.0	19.6	0.0	30.7	0.0	49.7	0.0	2
3	33.1	2.9	1.7	29.9	0.0	32.4	0.0	3
4	0.0	0.9	0.0	0.0	20.8	78.3	0.0	4
5	9.9	13.9	2.0	35.6	0.0	38.6	0.0	5
6	0.0	13.9	0.0	0.0	10.1	76.0	0.0	6
7	0.0	0.9	0.0	0.0	20.8	78.3	0.0	7
8	0.0	19.6	0.0	30.7	0.0	49.7	0.0	8
9	0.0	16.6	0.0	26.1	0.0	42.2	15.1	9
10	0.0	19.6	0.0	30.7	0.0	49.7	0.0	10
11	0.0	19.6	0.0	30.7	0.0	49.7	0.0	11
12	0.0	19.6	0.0	30.7	0.0	49.7	0.0	12

INPUT PARAMETERS:

NUMBER OF CELLS	79
CELL AREA , cm2	1070.0
GROSS POWER , kW	7.25
PARASITIC POWER CONSUMPTION , kW	2.25
ANODE UTILIZATION	0.75
CATHODE UTILIZATION	0.50
H2O/Methanol AT REFORMER INLET	1.10
EXCESS OXYGEN AT BURNER INLET	0.0%

OUTPUT PARAMETERS:

CELL VOLTAGE , mV	546.2
CURRENT DENSITY , mA/cm2	158.5
NET EFFICIENCY (LHV%)	24.1%
STACK HEAT LOAD , BTU/hr	31952.1
REFORMER HEAT LOAD , BTU/hr	6413.6
HEAT EX. HEAT LOAD , BTU/Hr	2421.9
BLOWER FLOW RATE , cu. ft/hr	803.2

MATERIAL AND ENERGY BALANCE
FULL LOAD AT H_2O/C = 1.1 and 75% ANODE UTILIZATION

ENERGY RESEARCH CORP.

DATE: 12-13-1984

NODE ARRAY ANALYSIS

CONFIGURATION #4

FLOW RATE - lb mole/hr

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	TOTAL	Press ATM	Temp Deg-F	Enthalpy BTU/hr	NODE
1	0.000	0.000	0.000	0.000	0.000	0.000	0.273	0.273	1.000	60	-2.5548E+04	1
2	0.000	0.300	0.000	0.401	0.000	0.753	0.000	1.454	1.000	300	-9.0482E+04	2
3	0.781	0.065	0.038	0.637	0.000	0.753	0.000	2.272	1.000	400	-1.0184E+05	3
4	0.000	0.023	0.000	0.000	0.546	2.055	0.000	2.625	1.000	250	1.0623E+04	4
5	0.234	0.264	0.038	0.637	0.000	0.753	0.000	1.925	1.000	350	-1.2495E+05	5
6	0.000	0.370	0.000	0.000	0.273	2.055	0.000	2.699	1.000	350	-2.2526E+04	6
7	0.000	0.006	0.000	0.000	0.136	0.511	0.000	0.653	1.000	70	1.8232E+03	7
8	0.000	0.504	0.000	0.674	0.000	1.264	0.000	2.442	1.000	965	-1.3790E+05	8
9	0.000	0.300	0.000	0.401	0.000	0.753	0.273	1.727	1.000	865	-1.0126E+05	9
10	0.000	0.504	0.000	0.674	0.000	1.264	0.000	2.442	1.000	500	-1.4792E+05	10
11	0.000	0.204	0.000	0.273	0.000	0.511	0.000	0.988	1.000	500	-5.9845E+04	11
12	0.000	0.300	0.000	0.401	0.000	0.753	0.000	1.454	1.000	500	-8.8076E+04	12

COMPOSITION - MOLE PERCENT

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	NODE
1	0.0	0.0	0.0	0.0	0.0	0.0	100.0	1
2	0.0	20.6	0.0	27.6	0.0	51.8	0.0	2
3	34.4	2.9	1.7	28.0	0.0	33.1	0.0	3
4	0.0	0.9	0.0	0.0	20.8	78.3	0.0	4
5	12.2	13.7	2.0	33.1	0.0	39.1	0.0	5
6	0.0	13.7	0.0	0.0	10.1	76.2	0.0	6
7	0.0	0.9	0.0	0.0	20.8	78.3	0.0	7
8	0.0	20.6	0.0	27.6	0.0	51.8	0.0	8
9	0.0	17.4	0.0	23.2	0.0	43.6	15.8	9
10	0.0	20.6	0.0	27.6	0.0	51.8	0.0	10
11	0.0	20.6	0.0	27.6	0.0	51.8	0.0	11
12	0.0	20.6	0.0	27.6	0.0	51.8	0.0	12

INPUT PARAMETERS:

NUMBER OF CELLS	79
CELL AREA , cm2	1070.0
GROSS POWER , kW	7.25
PARASITIC POWER CONSUMPTION , kW	2.25
ANODE UTILIZATION	0.70
CATHODE UTILIZATION	0.50
H2O/Methanol AT REFORMER INLET	1.10
EXCESS OXYGEN AT BURNER INLET	0.0%

OUTPUT PARAMETERS:

CELL VOLTAGE , mV	545.6
CURRENT DENSITY , mA/cm2	157.2
NET EFFICIENCY (LHV)	22.9%
STACK HEAT LOAD , BTU/hr	31514.4
REFORMER HEAT LOAD , BTU/hr	10605.6
HEAT EX. HEAT LOAD , BTU/hr	2496.1
BLOWER FLOW RATE , cu. ft/hr	806.9

MATERIAL AND ENERGY BALANCE
FULL LOAD AT H_2O/C = 1.1 and 70% ANODE UTILIZATION

ENERGY RESEARCH CORP.

DATE: 12-17-1984

NODE ARRAY ANALYSIS

CONFIGURATION #4

FLOW RATE - lb mole/hr

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	TOTAL	Press ATM	Temp Deg-F	Enthalpy BTU/hr	NODE
1	0.000	0.000	0.000	0.000	0.000	0.000	0.291	0.291	1.000	60	-2.7261E+04	1
2	0.000	0.320	0.000	0.371	0.000	0.792	0.000	1.483	1.000	300	-9.7254E+04	2
3	0.835	0.067	0.038	0.624	0.000	0.792	0.000	2.356	1.000	400	-9.9481E+04	3
4	0.000	0.023	0.000	0.000	0.543	2.042	0.000	2.607	1.000	250	1.0552E+04	4
5	0.292	0.272	0.038	0.624	0.000	0.792	0.000	2.019	1.000	350	-1.2316E+05	5
6	0.000	0.361	0.000	0.000	0.271	2.042	0.000	2.673	1.000	350	-2.1683E+04	6
7	0.000	0.007	0.000	0.000	0.165	0.621	0.000	0.794	1.000	70	2.2157E+03	7
8	0.000	0.571	0.000	0.662	0.000	1.414	0.000	2.647	1.000	1066	-1.3319E+05	8
9	0.000	0.320	0.000	0.371	0.000	0.792	0.291	1.774	1.000	966	-9.7267E+04	9
10	0.000	0.571	0.000	0.662	0.000	1.414	0.000	2.647	1.000	500	-1.5137E+05	10
11	0.000	0.251	0.000	0.291	0.000	0.621	0.000	1.164	1.000	500	-6.6550E+04	11
12	0.000	0.320	0.000	0.371	0.000	0.792	0.000	1.483	1.000	500	-9.4823E+04	12

COMPOSITION - MOLE PERCENT

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	NODE
1	0.0	0.0	0.0	0.0	0.0	0.0	100.0	1
2	0.0	21.6	0.0	25.0	0.0	53.4	0.0	2
3	35.4	2.9	1.6	26.5	0.0	33.6	0.0	3
4	0.0	0.9	0.0	0.0	20.8	78.3	0.0	4
5	14.5	13.5	1.9	30.9	0.0	39.2	0.0	5
6	0.0	13.5	0.0	0.0	10.2	76.4	0.0	6
7	0.0	0.9	0.0	0.0	20.8	78.3	0.0	7
8	0.0	21.6	0.0	25.0	0.0	53.4	0.0	8
9	0.0	18.0	0.0	20.9	0.0	44.6	16.4	9
10	0.0	21.6	0.0	25.0	0.0	53.4	0.0	10
11	0.0	21.6	0.0	25.0	0.0	53.4	0.0	11
12	0.0	21.6	0.0	25.0	0.0	53.4	0.0	12

INPUT PARAMETERS:

NUMBER OF CELLS	79
CELL AREA , cm2	1070.0
GROSS POWER , kW	7.25
PARASITIC POWER CONSUMPTION , kW	2.25
ANODE UTILIZATION	0.65
CATHODE UTILIZATION	0.50
H2O/Methanol AT REFORMER INLET	1.10
EXCESS OXYGEN AT BURNER INLET	0.0%

OUTPUT PARAMETERS:

CELL VOLTAGE , mV	549.3
CURRENT DENSITY , mA/cm2	156.1
NET EFFICIENCY (LHV)	21.3%
STACK HEAT LOAD , BTU/hr	31170.6
REFORMER HEAT LOAD , BTU/hr	15394.3
HEAT EX. HEAT LOAD , BTU/hr	2431.8
BLOWER FLOW RATE , cu. ft/hr	823.1

MATERIAL AND ENERGY BALANCE
FULL LOAD AT H_2O/C = 1.1 and 65% ANODE UTILIZATION

ENERGY RESEARCH CORP.

DATE: 12-13-1984

NODE ARRAY ANALYSIS

CONFIGURATION #4

FLOW RATE - lb mole/hr

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	TOTAL	Press ATM	Temp Deg-F	Enthalpy BTU/hr	NODE
1	0.000	0.000	0.000	0.000	0.000	0.000	0.242	0.242	1.000	60	-2.2676E+04	1
2	0.000	0.315	0.000	0.619	0.000	0.807	0.000	1.741	1.000	300	-1.2705E+05	2
3	0.698	0.101	0.028	0.833	0.000	0.807	0.000	2.467	1.000	400	-1.3681E+05	3
4	0.000	0.023	0.000	0.000	0.559	2.100	0.000	2.682	1.000	250	1.0855E+04	4
5	0.140	0.295	0.028	0.833	0.000	0.807	0.000	2.103	1.000	350	-1.5958E+05	5
6	0.000	0.388	0.000	0.000	0.279	2.100	0.000	2.767	1.000	350	-2.3948E+04	6
7	0.000	0.004	0.000	0.000	0.084	0.316	0.000	0.403	1.000	70	1.1263E+03	7
8	0.000	0.438	0.000	0.861	0.000	1.123	0.000	2.422	1.000	691	-1.6852E+05	8
9	0.000	0.315	0.000	0.619	0.000	0.807	0.242	1.983	1.000	591	-1.3965E+05	9
10	0.000	0.438	0.000	0.861	0.000	1.123	0.000	2.422	1.000	500	-1.7263E+05	10
11	0.000	0.123	0.000	0.242	0.000	0.316	0.000	0.681	1.000	500	-4.8544E+04	11
12	0.000	0.315	0.000	0.619	0.000	0.807	0.000	1.741	1.000	500	-1.2408E+05	12

COMPOSITION - MOLE PERCENT

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	NODE
1	0.0	0.0	0.0	0.0	0.0	0.0	100.0	1
2	0.0	18.1	0.0	35.5	0.0	46.4	0.0	2
3	28.3	4.1	1.2	33.7	0.0	32.7	0.0	3
4	0.0	0.9	0.0	0.0	20.8	78.3	0.0	4
5	6.6	14.0	1.3	39.6	0.0	38.4	0.0	5
6	0.0	14.0	0.0	0.0	10.1	75.9	0.0	6
7	0.0	0.9	0.0	0.0	20.8	78.3	0.0	7
8	0.0	18.1	0.0	35.5	0.0	46.4	0.0	8
9	0.0	15.9	0.0	31.2	0.0	40.7	12.2	9
10	0.0	18.1	0.0	35.5	0.0	46.4	0.0	10
11	0.0	18.1	0.0	35.5	0.0	46.4	0.0	11
12	0.0	18.1	0.0	35.5	0.0	46.4	0.0	12

INPUT PARAMETERS:

NUMBER OF CELLS	79
CELL AREA , cm2	1070.0
GROSS POWER , kW	7.25
PARASITIC POWER CONSUMPTION , kW	2.25
ANODE UTILIZATION	0.80
CATHODE UTILIZATION	0.50
H2O/Methanol AT REFORMER INLET	1.30
EXCESS OXYGEN AT BURNER INLET	0.0%

OUTPUT PARAMETERS:

CELL VOLTAGE , mV	533.9
CURRENT DENSITY , mA/cm2	160.6
NET EFFICIENCY (LHV)	25.7%
STACK HEAT LOAD , BTU/hr	32939.3
REFORMER HEAT LOAD , BTU/hr	1263.2
HEAT EX. HEAT LOAD , BTU/hr	2963.9
BLOWER FLOW RATE , cu. ft/hr	966.2

MATERIAL AND ENERGY BALANCE
FULL LOAD AT H_2O/C = 1.3 and 80% ANODE UTILIZATION

ENERGY RESEARCH CORP.

DATE: 12-13-1984

NODE ARRAY ANALYSIS

CONFIGURATION #4

FLOW RATE - lb mole/hr

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	TOTAL	Press ATM	Temp Deg-F	Enthalpy BTU/hr	NODE
1	0.000	0.000	0.000	0.000	0.000	0.000	0.255	0.255	1.000	60	-2.3850E+04	1
2	0.000	0.331	0.000	0.544	0.000	0.850	0.000	1.725	1.000	300	-1.1626E+05	2
3	0.737	0.104	0.027	0.772	0.000	0.850	0.000	2.489	1.000	400	-1.2669E+05	3
4	0.000	0.023	0.000	0.000	0.553	2.079	0.000	2.654	1.000	250	1.0743E+04	4
5	0.184	0.297	0.027	0.772	0.000	0.850	0.000	2.130	1.000	350	-1.4943E+05	5
6	0.000	0.382	0.000	0.000	0.276	2.079	0.000	2.737	1.000	350	-2.3510E+04	6
7	0.000	0.004	0.000	0.000	0.106	0.397	0.000	0.508	1.000	70	1.4170E+03	7
8	0.000	0.486	0.000	0.799	0.000	1.247	0.000	2.532	1.000	784	-1.6007E+05	8
9	0.000	0.331	0.000	0.544	0.000	0.850	0.255	1.980	1.000	684	-1.2806E+05	9
10	0.000	0.486	0.000	0.799	0.000	1.247	0.000	2.532	1.000	500	-1.6640E+05	10
11	0.000	0.155	0.000	0.255	0.000	0.397	0.000	0.807	1.000	500	-5.3032E+04	11
12	0.000	0.331	0.000	0.544	0.000	0.850	0.000	1.725	1.000	500	-1.1337E+05	12

COMPOSITION - MOLE PERCENT

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	NODE
1	0.0	0.0	0.0	0.0	0.0	0.0	100.0	1
2	0.0	19.2	0.0	31.6	0.0	49.3	0.0	2
3	29.6	4.2	1.1	31.0	0.0	34.1	0.0	3
4	0.0	0.9	0.0	0.0	20.8	78.3	0.0	4
5	8.6	14.0	1.3	36.2	0.0	39.9	0.0	5
6	0.0	14.0	0.0	0.0	10.1	75.9	0.0	6
7	0.0	0.9	0.0	0.0	20.8	78.3	0.0	7
8	0.0	19.2	0.0	31.6	0.0	49.3	0.0	8
9	0.0	16.7	0.0	27.5	0.0	42.9	12.9	9
10	0.0	19.2	0.0	31.6	0.0	49.3	0.0	10
11	0.0	19.2	0.0	31.6	0.0	49.3	0.0	11
12	0.0	19.2	0.0	31.6	0.0	49.3	0.0	12

INPUT PARAMETERS:

NUMBER OF CELLS	79
CELL AREA , cm2	1070.0
GROSS POWER , kW	7.25
PARASITIC POWER CONSUMPTION , kW	2.25
ANODE UTILIZATION	0.75
CATHODE UTILIZATION	0.50
H2O/Methanol AT REFORMER INLET	1.30
EXCESS OXYGEN AT BURNER INLET	0.0%

OUTPUT PARAMETERS:

CELL VOLTAGE , mV	539.5
CURRENT DENSITY , mA/cm2	159.0
NET EFFICIENCY (LHV)	24.4%
STACK HEAT LOAD , BTU/hr	32244.3
REFORMER HEAT LOAD , BTU/hr	4969.5
HEAT EX. HEAT LOAD , BTU/hr	2894.6
BLOWER FLOW RATE , cu. ft/hr	957.3

MATERIAL AND ENERGY BALANCE
FULL LOAD AT H_2O/C = 1.3 and 75% ANODE UTILIZATION

ENERGY RESEARCH CORP.

DATE: 12-13-1984

NODE ARRAY ANALYSIS

CONFIGURATION #4

FLOW RATE - lb mole/hr

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	TOTAL	Press ATM	Temp Deg-F	Enthalpy BTU/hr	NODE
1	0.000	0.000	0.000	0.000	0.000	0.000	0.270	0.270	1.000	60	-2.5262E+04	1
2	0.000	0.351	0.000	0.490	0.000	0.893	0.000	1.734	1.000	300	-1.0913E+05	2
3	0.783	0.107	0.026	0.734	0.000	0.893	0.000	2.543	1.000	400	-1.2031E+05	3
4	0.000	0.023	0.000	0.000	0.548	2.061	0.000	2.632	1.000	250	1.0652E+04	4
5	0.235	0.303	0.026	0.734	0.000	0.893	0.000	2.191	1.000	350	-1.4323E+05	5
6	0.000	0.375	0.000	0.000	0.274	2.061	0.000	2.710	1.000	350	-2.2948E+04	6
7	0.000	0.005	0.000	0.000	0.131	0.491	0.000	0.627	1.000	70	1.7516E+03	7
8	0.000	0.544	0.000	0.760	0.000	1.385	0.000	2.688	1.000	878	-1.5577E+05	8
9	0.000	0.351	0.000	0.490	0.000	0.893	0.270	2.004	1.000	778	-1.2010E+05	9
10	0.000	0.544	0.000	0.760	0.000	1.385	0.000	2.688	1.000	500	-1.6469E+05	10
11	0.000	0.193	0.000	0.270	0.000	0.491	0.000	0.954	1.000	500	-5.8440E+04	11
12	0.000	0.351	0.000	0.490	0.000	0.893	0.000	1.734	1.000	500	-1.0625E+05	12

COMPOSITION - MOLE PERCENT

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	NODE
1	0.0	0.0	0.0	0.0	0.0	0.0	100.0	1
2	0.0	20.2	0.0	28.3	0.0	51.5	0.0	2
3	30.8	4.2	1.0	28.8	0.0	35.1	0.0	3
4	0.0	0.9	0.0	0.0	20.8	78.3	0.0	4
5	10.7	13.8	1.2	33.5	0.0	40.8	0.0	5
6	0.0	13.8	0.0	0.0	10.1	76.1	0.0	6
7	0.0	0.9	0.0	0.0	20.8	78.3	0.0	7
8	0.0	20.2	0.0	28.3	0.0	51.5	0.0	8
9	0.0	17.5	0.0	24.5	0.0	44.6	13.5	9
10	0.0	20.2	0.0	28.3	0.0	51.5	0.0	10
11	0.0	20.2	0.0	28.3	0.0	51.5	0.0	11
12	0.0	20.2	0.0	28.3	0.0	51.5	0.0	12

INPUT PARAMETERS:

NUMBER OF CELLS	79
CELL AREA , cm2	1070.0
GROSS POWER , kW	7.25
PARASITIC POWER CONSUMPTION , kW	2.25
ANODE UTILIZATION	0.70
CATHODE UTILIZATION	0.50
H2O/Methanol AT REFORMER INLET	1.30
EXCESS OXYGEN AT BURNER INLET	0.0%

OUTPUT PARAMETERS:

CELL VOLTAGE , mV	544.1
CURRENT DENSITY , mA/cm2	157.6
NET EFFICIENCY (LHV)	23.0%
STACK HEAT LOAD , BTU/hr	31781.1
REFORMER HEAT LOAD , BTU/hr	9129.4
HEAT EX. HEAT LOAD , BTU/hr	2875.8
BLOWER FLOW RATE , cu. ft/hr	962.4

MATERIAL AND ENERGY BALANCE
FULL LOAD AT H_2O/C = 1.3 and 75% ANODE UTILIZATION

ENERGY RESEARCH CORP.

DATE: 12-13-1984

NODE ARRAY ANALYSIS

CONFIGURATION #4

FLOW RATE - lb mole/hr

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	TOTAL	Press ATM	Temp Deg-F	Enthalpy BTU/hr	NODE
1	0.000	0.000	0.000	0.000	0.000	0.000	0.288	0.288	1.000	60	-2.6949E+04	1
2	0.000	0.374	0.000	0.452	0.000	0.943	0.000	1.769	1.000	300	-1.0488E+05	2
3	0.837	0.113	0.026	0.714	0.000	0.943	0.000	2.632	1.000	400	-1.1692E+05	3
4	0.000	0.023	0.000	0.000	0.544	2.046	0.000	2.613	1.000	250	1.0577E+04	4
5	0.293	0.313	0.026	0.714	0.000	0.943	0.000	2.288	1.000	350	-1.4025E+05	5
6	0.000	0.367	0.000	0.000	0.272	2.046	0.000	2.685	1.000	350	-2.2253E+04	6
7	0.000	0.007	0.000	0.000	0.160	0.600	0.000	0.766	1.000	70	2.1400E+03	7
8	0.000	0.612	0.000	0.740	0.000	1.543	0.000	2.895	1.000	973	-1.5491E+05	8
9	0.000	0.374	0.000	0.452	0.000	0.943	0.288	2.057	1.000	873	-1.1502E+05	9
10	0.000	0.612	0.000	0.740	0.000	1.543	0.000	2.895	1.000	500	-1.6688E+05	10
11	0.000	0.239	0.000	0.288	0.000	0.600	0.000	1.126	1.000	500	-6.4911E+04	11
12	0.000	0.374	0.000	0.452	0.000	0.943	0.000	1.769	1.000	500	-1.0197E+05	12

COMPOSITION - MOLE PERCENT

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	NODE
1	0.0	0.0	0.0	0.0	0.0	0.0	100.0	1
2	0.0	21.1	0.0	25.6	0.0	53.3	0.0	2
3	31.8	4.3	1.0	27.1	0.0	35.8	0.0	3
4	0.0	0.9	0.0	0.0	20.8	78.3	0.0	4
5	12.8	13.7	1.1	31.2	0.0	41.2	0.0	5
6	0.0	13.7	0.0	0.0	10.1	76.2	0.0	6
7	0.0	0.9	0.0	0.0	20.8	78.3	0.0	7
8	0.0	21.1	0.0	25.6	0.0	53.3	0.0	8
9	0.0	18.2	0.0	22.0	0.0	45.8	14.0	9
10	0.0	21.1	0.0	25.6	0.0	53.3	0.0	10
11	0.0	21.1	0.0	25.6	0.0	53.3	0.0	11
12	0.0	21.1	0.0	25.6	0.0	53.3	0.0	12

INPUT PARAMETERS:

NUMBER OF CELLS	79
CELL AREA , cm2	1070.0
GROSS POWER , kW	7.25
PARASITIC POWER CONSUMPTION , kW	2.25
ANODE UTILIZATION	0.65
CATHODE UTILIZATION	0.50
H2O/Methanol AT REFORMER INLET	1.30
EXCESS OXYGEN AT BURNER INLET	0.0%

OUTPUT PARAMETERS:

CELL VOLTAGE , mV	548.0
CURRENT DENSITY , mA/cm2	156.5
NET EFFICIENCY (LHV)	21.6%
STACK HEAT LOAD , BTU/hr	31417.8
REFORMER HEAT LOAD , BTU/hr	13867.4
HEAT EX. HEAT LOAD , BTU/hr	2904.7
BLOWER FLOW RATE , cu. ft/hr	981.7

MATERIAL AND ENERGY BALANCE
FULL LOAD AT H_2O/C = 1.3 and 65% ANODE UTILIZATION

ENERGY RESEARCH CORP.

DATE: 12-13-1984

NODE ARRAY ANALYSIS

CONFIGURATION #4

FLOW RATE - lb mole/hr

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	TOTAL	Press ATM	Temp Deg-F	Enthalpy BTU/hr	NODE
1	0.000	0.000	0.000	0.000	0.000	0.000	0.241	0.241	1.000	60	-2.2601E+04	1
2	0.000	0.362	0.000	0.738	0.000	0.938	0.000	2.038	1.000	300	-1.5031E+05	2
3	0.701	0.144	0.023	0.956	0.000	0.938	0.000	2.762	1.000	400	-1.5987E+05	3
4	0.000	0.023	0.000	0.000	0.561	2.109	0.000	2.693	1.000	250	1.0901E+04	4
5	0.140	0.337	0.023	0.956	0.000	0.938	0.000	2.394	1.000	350	-1.8272E+05	5
6	0.000	0.391	0.000	0.000	0.280	2.109	0.000	2.781	1.000	350	-2.4194E+04	6
7	0.000	0.003	0.000	0.000	0.082	0.307	0.000	0.392	1.000	70	1.0943E+03	7
8	0.000	0.480	0.000	0.979	0.000	1.245	0.000	2.705	1.000	644	-1.9141E+05	8
9	0.000	0.362	0.000	0.738	0.000	0.938	0.241	2.279	1.000	544	-1.6313E+05	9
10	0.000	0.480	0.000	0.979	0.000	1.245	0.000	2.705	1.000	500	-1.9486E+05	10
11	0.000	0.119	0.000	0.241	0.000	0.307	0.000	0.667	1.000	500	-4.8026E+04	11
12	0.000	0.362	0.000	0.738	0.000	0.938	0.000	2.038	1.000	500	-1.4683E+05	12

COMPOSITION - MOLE PERCENT

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	NODE
1	0.0	0.0	0.0	0.0	0.0	0.0	100.0	1
2	0.0	17.8	0.0	36.2	0.0	46.0	0.0	2
3	25.4	5.2	0.8	34.6	0.0	34.0	0.0	3
4	0.0	0.9	0.0	0.0	20.8	78.3	0.0	4
5	5.9	14.1	1.0	39.9	0.0	39.2	0.0	5
6	0.0	14.1	0.0	0.0	10.1	75.9	0.0	6
7	0.0	0.9	0.0	0.0	20.8	78.3	0.0	7
8	0.0	17.8	0.0	36.2	0.0	46.0	0.0	8
9	0.0	15.9	0.0	32.4	0.0	41.2	10.6	9
10	0.0	17.8	0.0	36.2	0.0	46.0	0.0	10
11	0.0	17.8	0.0	36.2	0.0	46.0	0.0	11
12	0.0	17.8	0.0	36.2	0.0	46.0	0.0	12

INPUT PARAMETERS:

NUMBER OF CELLS	79
CELL AREA , cm2	1070.0
GROSS POWER , kW	7.25
PARASITIC POWER CONSUMPTION , kW	2.25
ANODE UTILIZATION	0.80
CATHODE UTILIZATION	0.50
H2O/Methanol AT REFORMER INLET	1.50
EXCESS OXYGEN AT BURNER INLET	0.0%

OUTPUT PARAMETERS:

CELL VOLTAGE , mV	531.6
CURRENT DENSITY , mA/cm2	161.3
NET EFFICIENCY (LHV)	25.7%
STACK HEAT LOAD , BTU/hr	33198.2
REFORMER HEAT LOAD , BTU/hr	197.6
HEAT EX. HEAT LOAD , BTU/hr	3477.0
BLOWER FLOW RATE , cu. ft/hr	1131.1

MATERIAL AND ENERGY BALANCE
FULL LOAD AT H_2O/C = 1.5 and 80% ANODE UTILIZATION

ENERGY RESEARCH CORP.

DATE: [illegible]

NODE ARRAY ANALYSIS

CONFIGURATION #4

FLOW RATE - lb mole/hr

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	TOTAL	Press ATM	Temp Deg-F	Enthalpy BTU/hr	NODE
1	0.000	0.000	0.000	0.000	0.000	0.000	0.254	0.254	1.000	60	-2.[illegible]	1
2	0.000	0.381	0.000	0.649	0.000	0.994	0.000	2.024	1.000	300	-1.[illegible]	2
3	0.740	0.149	0.022	0.882	0.000	0.994	0.000	2.786	1.000	400	-1.[illegible]	3
4	0.000	0.023	0.000	0.000	0.555	2.087	0.000	2.665	1.000	250	-1.[illegible]	4
5	0.185	0.340	0.022	0.882	0.000	0.994	0.000	2.423	1.000	350	-1.[illegible]	5
6	0.000	0.386	0.000	0.000	0.277	2.087	0.000	2.751	1.000	350	-2.[illegible]	6
7	0.000	0.004	0.000	0.000	0.103	0.389	0.000	0.496	1.000	70	-1.[illegible]	7
8	0.000	0.530	0.000	0.903	0.000	1.383	0.000	2.815	1.000	728	-1.[illegible]	8
9	0.000	0.381	0.000	0.649	0.000	0.994	0.254	2.278	1.000	628	-1.[illegible]	9
10	0.000	0.530	0.000	0.903	0.000	1.383	0.000	2.815	1.000	500	-1.[illegible]	10
11	0.000	0.149	0.000	0.254	0.000	0.389	0.000	0.791	1.000	500	-5.[illegible]	11
12	0.000	0.381	0.000	0.649	0.000	0.994	0.000	2.024	1.000	500	-1.[illegible]	12

COMPOSITION - MOLE PERCENT

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	NODE
1	0.0	0.0	0.0	0.0	0.0	0.0	100.0	1
2	0.0	18.8	0.0	32.1	0.0	49.1	0.0	2
3	26.6	5.3	0.8	31.6	0.0	35.7	0.0	3
4	0.0	0.9	0.0	0.0	20.8	78.3	0.0	4
5	7.6	14.0	0.9	36.4	0.0	41.0	0.0	5
6	0.0	14.0	0.0	0.0	10.1	75.9	0.0	6
7	0.0	0.9	0.0	0.0	20.8	78.3	0.0	7
8	0.0	18.8	0.0	32.1	0.0	49.1	0.0	8
9	0.0	16.7	0.0	28.5	0.0	43.6	11.1	9
10	0.0	18.8	0.0	32.1	0.0	49.1	0.0	10
11	0.0	18.8	0.0	32.1	0.0	49.1	0.0	11
12	0.0	18.8	0.0	32.1	0.0	49.1	0.0	12

INPUT PARAMETERS:

NUMBER OF CELLS	79
CELL AREA , cm2	1070.0
GROSS POWER , kW	7.25
PARASITIC POWER CONSUMPTION , kW	2.25
ANODE UTILIZATION	0.75
CATHODE UTILIZATION	0.50
H2O/Methanol AT REFORMER INLET	1.50
EXCESS OXYGEN AT BURNER INLET	0.0%

OUTPUT PARAMETERS:

CELL VOLTAGE , mV	537.3
CURRENT DENSITY , mA/cm2	159.6
NET EFFICIENCY (LHV)	24.5%
STACK HEAT LOAD , BTU/hr	[illegible]
REFORMER HEAT LOAD , BTU/hr	3920.1
HEAT EX. HEAT LOAD , BTU/hr	3402.0
BLOWER FLOW RATE , cu. ft/hr	2123.4

MATERIAL AND ENERGY BALANCE
FULL LOAD AT H_2O/C = 1.5 and 75% ANODE UTILIZATION

ENERGY RESEARCH CORP.

DATE: 12-13-1984

NODE ARRAY ANALYSIS

CONFIGURATION #4

FLOW RATE - lb mole/hr

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	TOTAL	Press ATM	Temp Deg-F	Enthalpy BTU/hr	NODE
1	0.000	0.000	0.000	0.000	0.000	0.000	0.269	0.269	1.000	60	-2.5178E+04	1
2	0.000	0.403	0.000	0.585	0.000	1.050	0.000	2.038	1.000	300	-1.2881E+05	2
3	0.786	0.155	0.021	0.833	0.000	1.050	0.000	2.844	1.000	400	-1.3979E+05	3
4	0.000	0.023	0.000	0.000	0.550	2.069	0.000	2.642	1.000	250	1.0692E+04	4
5	0.236	0.347	0.021	0.833	0.000	1.050	0.000	2.487	1.000	350	-1.6250E+05	5
6	0.000	0.381	0.000	0.000	0.275	2.069	0.000	2.724	1.000	350	-2.3452E+04	6
7	0.000	0.005	0.000	0.000	0.128	0.482	0.000	0.616	1.000	70	1.7200E+03	7
8	0.000	0.589	0.000	0.854	0.000	1.532	0.000	2.975	1.000	816	-1.7486E+05	8
9	0.000	0.403	0.000	0.585	0.000	1.050	0.269	2.307	1.000	716	-1.3990E+05	9
10	0.000	0.589	0.000	0.854	0.000	1.532	0.000	2.975	1.000	500	-1.8306E+05	10
11	0.000	0.185	0.000	0.269	0.000	0.482	0.000	0.937	1.000	500	-5.7639E+04	11
12	0.000	0.403	0.000	0.585	0.000	1.050	0.000	2.038	1.000	500	-1.2542E+05	12

COMPOSITION - MOLE PERCENT

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	NODE
1	0.0	0.0	0.0	0.0	0.0	0.0	100.0	1
2	0.0	19.8	0.0	28.7	0.0	51.5	0.0	2
3	27.6	5.5	0.7	29.3	0.0	36.9	0.0	3
4	0.0	0.9	0.0	0.0	20.8	78.3	0.0	4
5	9.5	14.0	0.8	33.5	0.0	42.2	0.0	5
6	0.0	14.0	0.0	0.0	10.1	75.9	0.0	6
7	0.0	0.9	0.0	0.0	20.8	78.3	0.0	7
8	0.0	19.8	0.0	28.7	0.0	51.5	0.0	8
9	0.0	17.5	0.0	25.4	0.0	45.5	11.7	9
10	0.0	19.8	0.0	28.7	0.0	51.5	0.0	10
11	0.0	19.8	0.0	28.7	0.0	51.5	0.0	11
12	0.0	19.8	0.0	28.7	0.0	51.5	0.0	12

INPUT PARAMETERS:

NUMBER OF CELLS	79
CELL AREA , cm2	1070.0
GROSS POWER , kW	7.25
PARASITIC POWER CONSUMPTION , kW	2.25
ANODE UTILIZATION	0.70
CATHODE UTILIZATION	0.50
H2O/Methanol AT REFORMER INLET	1.50
EXCESS OXYGEN AT BURNER INLET	0.0%

OUTPUT PARAMETERS:

CELL VOLTAGE , mV	542.1
CURRENT DENSITY , mA/cm2	158.2
NET EFFICIENCY (LHV)	23.1%
STACK HEAT LOAD , BTU/hr	32113.7
REFORMER HEAT LOAD , BTU/hr	8083.8
HEAT EX. HEAT LOAD , BTU/hr	3383.0
BLOWER FLOW RATE , cu. ft/hr	1131.0

MATERIAL AND ENERGY BALANCE
FULL LOAD AT H_2O/C = 1.5 and 70% ANODE UTILIZATION

ENERGY RESEARCH CORP.

DATE: 12-13-1984

NODE ARRAY ANALYSIS

CONFIGURATION #4

FLOW RATE - lb mole/hr

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	TOTAL	Press ATM	Temp Deg-F	Enthalpy BTU/hr	NODE
1	0.000	0.000	0.000	0.000	0.000	0.000	0.287	0.287	1.000	60	-2.6858E+04	1
2	0.000	0.430	0.000	0.539	0.000	1.111	0.000	2.080	1.000	300	-1.2356E+05	2
3	0.840	0.164	0.020	0.805	0.000	1.111	0.000	2.940	1.000	400	-1.3540E+05	3
4	0.000	0.023	0.000	0.000	0.546	2.054	0.000	2.622	1.000	250	1.0614E+04	4
5	0.294	0.359	0.020	0.805	0.000	1.111	0.000	2.589	1.000	350	-1.5836E+05	5
6	0.000	0.374	0.000	0.000	0.273	2.054	0.000	2.700	1.000	350	-2.2903E+04	6
7	0.000	0.007	0.000	0.000	0.157	0.591	0.000	0.755	1.000	70	2.1078E+03	7
8	0.000	0.659	0.000	0.826	0.000	1.702	0.000	3.187	1.000	903	-1.7291E+05	8
9	0.000	0.430	0.000	0.539	0.000	1.111	0.287	2.367	1.000	803	-1.3377E+05	9
10	0.000	0.659	0.000	0.826	0.000	1.702	0.000	3.187	1.000	500	-1.8409E+05	10
11	0.000	0.229	0.000	0.287	0.000	0.591	0.000	1.107	1.000	500	-6.3943E+04	11
12	0.000	0.430	0.000	0.539	0.000	1.111	0.000	2.080	1.000	500	-1.2015E+05	12

COMPOSITION - MOLE PERCENT

NODE	H2	H2O	CO	CO2	O2	N2	CH3OH	NODE
1	0.0	0.0	0.0	0.0	0.0	0.0	100.0	1
2	0.0	20.7	0.0	25.9	0.0	53.4	0.0	2
3	28.6	5.6	0.7	27.4	0.0	37.8	0.0	3
4	0.0	0.9	0.0	0.0	20.8	78.3	0.0	4
5	11.4	13.8	0.8	31.1	0.0	42.9	0.0	5
6	0.0	13.8	0.0	0.0	10.1	76.0	0.0	6
7	0.0	0.9	0.0	0.0	20.8	78.3	0.0	7
8	0.0	20.7	0.0	25.9	0.0	53.4	0.0	8
9	0.0	18.2	0.0	22.8	0.0	46.9	12.1	9
10	0.0	20.7	0.0	25.9	0.0	53.4	0.0	10
11	0.0	20.7	0.0	25.9	0.0	53.4	0.0	11
12	0.0	20.7	0.0	25.9	0.0	53.4	0.0	12

INPUT PARAMETERS:

NUMBER OF CELLS	79
CELL AREA , cm2	1070.0
GROSS POWER , kW	7.25
PARASITIC POWER CONSUMPTION , kW	2.25
ANODE UTILIZATION	0.65
CATHODE UTILIZATION	0.50
H2O/Methanol AT REFORMER INLET	1.50
EXCESS OXYGEN AT BURNER INLET	0.0%

OUTPUT PARAMETERS:

CELL VOLTAGE , mV	546.1
CURRENT DENSITY , mA/cm2	157.1
NET EFFICIENCY (LHV)	21.7%
STACK HEAT LOAD , BTU/hr	31735.7
REFORMER HEAT LOAD , BTU/hr	12813.0
HEAT EX. HEAT LOAD , BTU/hr	3417.6
BLOWER FLOW RATE , cu. ft/hr	1154.2

MATERIAL AND ENERGY BALANCE
FULL LOAD AT H_{2O}/C = 1.5 and 65% ANODE UTILIZATION

APPENDIX B

THERMODYNAMIC PROPERTIES OF METHANOL

Some Thermodynamic Properties of Methanol

Temperature °F	Vapor Pressure, lb/in²abs	Saturated Liquid: Specific Volume, ft³/lb	Saturated Liquid: Enthalpy, Btu/lb	Saturated Liquid: Entropy Btu/lb °F	Heat of Vaporization, Btu/lb	Saturated Vapor: Specific Volume, ft³/lb	Saturated Vapor: Enthalpy Btu/lb	Saturated Vapor: Entropy Btu/lb °F
32	0.571	0.0198	0.0	0.0000	516.0	283.7	516.0	1.050
40	0.755	0.0199	4.5	0.0098	513.8	215.6	518.3	1.038
50	1.05	0.0200	10.2	0.0210	511.1	159.7	521.3	1.024
60	1.44	0.0202	16.0	0.0322	508.1	118.6	524.1	1.010
70	1.95	0.0203	21.8	0.043	504.9	88.5	526.7	0.996
80	2.61	0.0204	27.8	0.054	501.4	67.2	529.2	0.983
90	3.47	0.0206	33.9	0.065	497.8	51.1	531.7	0.971
100	4.55	0.0207	39.9	0.076	494.1	39.6	534.0	0.959
110	5.90	0.0208	46.2	0.087	490.1	31.1	536.3	0.947
120	7.53	0.0210	52.6	0.098	485.9	24.6	538.5	0.937
130	9.60	0.0211	59.1	0.110	481.5	19.63	540.6	0.926
140	12.1	0.0212	65.7	0.120	477.1	15.72	542.8	0.916
150	15.2	0.0214	72.4	0.131	472.4	12.75	544.8	0.906
160	18.7	0.0216	79.2	0.142	467.5	10.40	546.7	0.897
170	23.0	0.0217	86.2	0.153	462.4	8.54	548.6	0.888
180	28.1	0.0219	93.2	0.164	457.1	7.06	550.3	0.879
190	34.1	0.0221	100.5	0.176	451.5	5.89	552.0	0.871
200	41.1	0.0222	107.9	0.187	445.7	4.92	553.6	0.863
210	49.1	0.0224	115.3	0.198	439.8	4.14	555.1	0.855
220	58.4	0.0226	122.9	0.209	433.7	3.49	556.6	0.848
230	69.0	0.0228	130.5	0.220	427.4	2.97	557.9	0.840
240	81.0	0.0231	138.5	0.232	420.7	2.53	559.2	0.833
250	95.0	0.0233	146.6	0.243	413.8	2.18	560.4	0.826
260	110	0.0236	154.8	0.254	406.7	1.87	561.5	0.820
270	127	0.0238	162.9	0.265	399.5	1.62	562.4	0.813
280	147	0.0241	171.1	0.275	392.2	1.406	563.3	0.806
290	169	0.0244	179.8	0.287	384.3	1.220	564.1	0.800
300	194	0.0247	188.9	0.299	376.0	1.056	564.9	0.794
310	221	0.0250	198.6	0.312	366.7	0.918	565.3	0.788
320	251	0.0253	208.2	0.325	357.1	0.802	565.3	0.783
330	284	0.0257	217.2	0.336	347.4	0.703	564.6	0.776
340	321	0.0261	225.5	0.346	336.8	0.620	562.3	0.767
350	361	0.0265	232.9	0.355	325.7	0.542	558.6	0.757
360	404	0.0270	239.5	0.363	314.4	0.476	553.9	0.747
370	451	0.0275	245.7	0.370	303.1	0.419	548.8	0.735
380	503	0.0281	252.7	0.378	290.3	0.369	543.0	0.724
390	560	0.0288	260.2	0.387	276.4	0.324	536.6	0.712
400	622	0.0296	268.6	0.397	261.1	0.284	529.7	0.700
410	690	0.0306	279.1	0.408	242.6	0.246	521.7	0.687
420	764	0.0318	291.0	0.421	222.0	0.212	513.0	0.674
430	844	0.0332	305.6	0.437	197.9	0.181	503.5	0.660
440	930	0.0349	321.9	0.455	170.9	0.151	492.8	0.645
450	1023	0.0375	340	0.475	138.0	0.122	478	0.630
460	1124	0.0437	363	0.499	92.0	0.085	455	0.599
464	1155	0.0590	440	0.582	0.0	0.059	440	0.582

J. M. Smith, *Chem. Eng. Prog.* 44, 521 (1948). Reprinted by permission

SOURCE: IMC METHANOL: A COMPLETE GUIDE

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AD-A163 636 FUEL PROCESSING SYSTEM FOR A 5KW METHANOL FUEL CELL POWER UNIT(U) ENERGY RESEARCH CORP DANBURY CT G STEINFELD 27 NOV 85 DAAK70-84-C-0099 2/2

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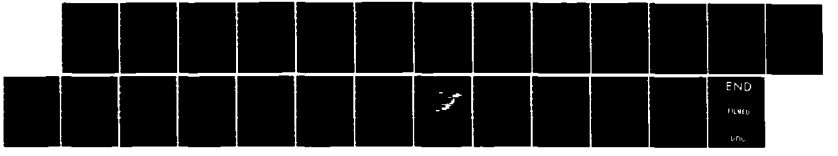

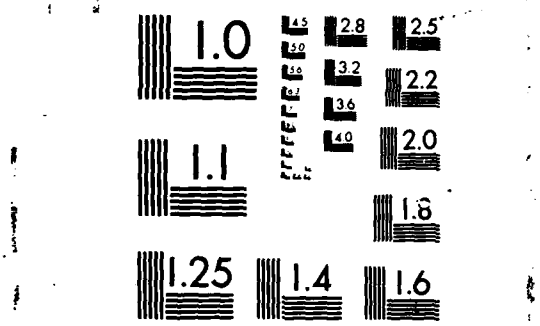

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APPENDIX C

PRESSURE DROP CALCULATIONS

PRESSURE DROP CALCULATIONS

The pressure drop of the reformer, and the combustion section of the reformer are important parameters in a fuel cell power plant. The combustion section of the reformer is fed low pressure anode exhaust which is burned and passed through the combustion annuli. In order to minimize pressure boosting by blowers, a minimum pressure drop is desired. Normally no pressure boosting is required in this stream. The vaporizer and catalyst bed section of the reformer are fed by a liquid pump for methanol and a recycle blower for the recycle gas. In order to minimize the pressure boost requirement for the recycle blower, minimum pressure drops are desired for the vaporizer and catalyst bed as well.

The complicating factor in addition to these considerations is that there is a relationship between pressure drop in a system and heat transfer in the same system. Ideally, a low pressure drop and high heat transfer is desired. However, due to the turbulence created in fluid flow as pressure drop increases, there is an increase in heat transfer as well. Colburn defined this relationship as follows (under conditions of turbulent flow):

$$\frac{h}{C_p} = 341\ D^{0.33} \left(\frac{\rho \Delta p}{L}\right)^{0.44}$$

where

h = heat transfer coefficient (BTU/Ft^2 HR ^oF)
D = Diameter (inches)
ρ = density (lb/ft^3)
ΔP = inches of water
L = length (ft)
C_p = heat capacity BTU/lb ^oF

Figure C-1 depicts plots of the above equation for tubes of 1 and 3 inches. The equation and the plot show that for a given size pipe, as the mass velocity is increased, the heat transfer rate goes up with 0.44 power of the pressure drop.

For cored tubes containing a centrally located cylindrical core or plug, the above equation applies if D is defined as the equivalent diameter or clearance. For a given mass rate through an empty tube or annulus, an increase in velocity caused by inserting a core in the pipe gives results represented by the following equation.

$$\frac{h}{C_p} = 615\, m^{0.125}\, \frac{(d_p - d_c)}{d_p - d_c}^{0.125}\, \left(\frac{\rho \Delta P}{L}\right)^{0.345}$$

where m = total mass flow per tube (lbs/sec)

d_p = diameter of pipe

d_c = diameter of core

Therefore, it has been shown that pressure drop does have a bearing on heat transfer. Figure C-1 does show, however, that baffled tubes result in higher heat transfer coefficients that are not much lower than packed tubes but result in much lower pressure drop. This provides an incentive for improving heat transfer in the reformer by baffles or extended surfaces.

For the purpose of this design, various reformer diameter annuli were examined in order to determine a desirable size which would provide both sufficient heat transfer area and reasonable pressure drop.

Pressure drop of the various annuli at different diameters were calculated based on the equivalent diameter of a tube having an equal cross-sectional area as the annulus in question. A

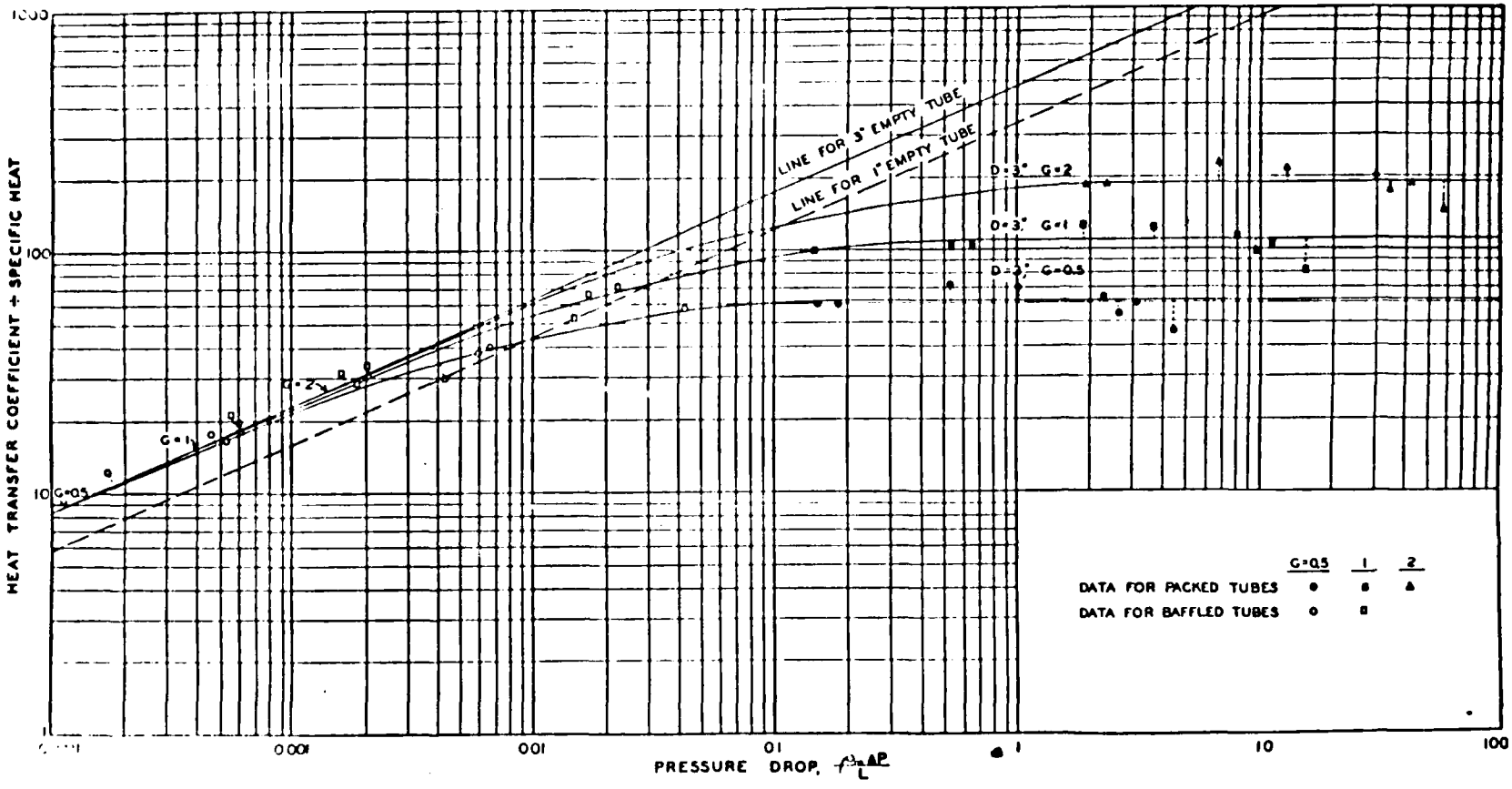


FIGURE C-1

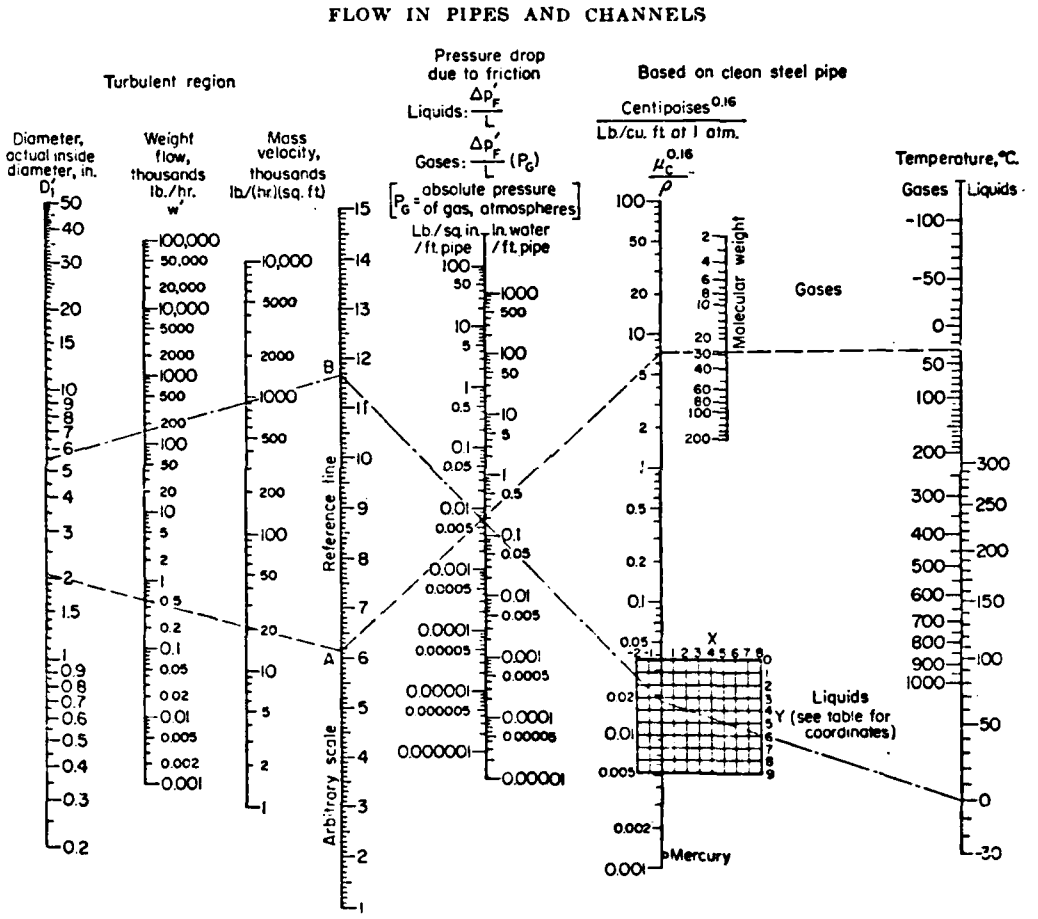
RELATIONSHIP BETWEEN HEAT TRANSFER COEFFICIENT AND PRESSURE DROP IN EMPTY, BAFFLED AND PACKED TUBES.

SOURCE: Colburn, A.P. Heat Transfer and Pressure Drop in Empty, Baffled and Packed Tubes, Trans AICHE V26, 1931, p166.

nomograph such as depicted in Table C-1 was used to estimate expected pressure drops in each empty annulus of the reformer. For packed annuli, namely the reforming annulus containing the reforming catalyst, a different method was used. Table C-2 shows the equation and parameters used for determining the pressure drop in the packed annulus.

After evaluating various diameters for the reformer, the sizes shown in Table C-4 were chosen. These were chosen for their ability to provide sufficient heat transfer area and low pressure drop in the combustion annulus and in the vaporizor and reforming annuli.

TABLE C-1
PRESSURE DROP IN PIPES



SOURCE: Perry, R.H. Chilton, C.H., Kirpatrick, S.D., Chemical Engineers' Handbook, Fourth Edition 1963, p. 5-23

TABLE C-2

PRESSURE DROP THROUGH PACKED BEDS

Pressure drop data for fixed beds have been correlated by Carmen [*Trans. Inst. Chem. Eng.* **15**, 150 (1937)], where the symbols are defined. He plotted a pressure drop term against Reynolds number.

That is $\frac{\Delta P e^3}{h s_0 (1-e) \rho u^2}$ against $(Re) = \frac{u\rho}{s_0 \mu (1-e)}$

The correlation can be rearranged and expressed in more readily available units with the result that

$$\Delta P = Bh^3 S^2 M T / P$$

where B = a quantity derived from a table by reference to the value of SMh/μ,
S = space velocity (h^{-1}),
M = average molecular weight of gas,
h = height of bed (feet or metres),
μ = viscosity of gas (lb ft^{-1} h^{-1} or centipoises),
T = average temperature of gas in reactor (Rankine or Kelvin),
P = average pressure in reactor [lb/in^2 (abs.) or kg cm^{-2} (abs.)].

ΔP is obtained in lb/in^2 or kg cm^{-2}. The factor B is dependent on SMh/μ.

To calculate a pressure drop, first calculate M/μ (see table 15), and evaluate SMh/μ, and then obtain B in ft lb h units from table 14a, or in metric units from table 14b. Substitution of the value of B in the equation given above gives the required pressure drop.

The values of pressure drop calculated from tables 14a and b are those expected in beds of packed catalyst. In use the bed packs down, causing the voidage in the bed to decrease and the pressure drop to increase to these expected values.

Some typical values of M/μ are given in table C-3.

Pressure drop

Catalyst size Dia. × length, or dia	3 × 3 mm	5·4 × 3·6 mm	5 × 5 mm	6 × 6 mm	8 × 8 mm	10 × 10 mm	8·5 × 11·3 mm	17 × 17 mm	17 × 17 mm	¼ - ⅜ in	½ - ⅝ in
Shape	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	ring	ring	spheres	granules
ICI Catalyst No.		11-3, 15·5, 41-3, 52-1					15-4	46-1, 57-1 Tubular reformer	54-2	32-4	35-4
SMh/μ (ft lb h)	Values of B in ft lb h units										
2.0×10^6	9.0×10^{-13}	4.4×10^{-13}	7.5×10^{-13}	5.2×10^{-13}	3.2×10^{-13}	2.2×10^{-13}	1.4×10^{-13}	9.4×10^{-14}	5.6×10^{-14}	4.4×10^{-13}	4.0×10^{-13}
3.0×10^6	5.6×10^{-13}	3.1×10^{-13}	5.4×10^{-13}	4.2×10^{-13}	2.5×10^{-13}	1.8×10^{-13}	1.2×10^{-13}	7.9×10^{-14}	4.7×10^{-14}	3.1×10^{-13}	3.3×10^{-13}
6.0×10^6	4.0×10^{-13}	2.5×10^{-13}	3.7×10^{-13}	2.8×10^{-13}	2.0×10^{-13}	1.5×10^{-13}	1.0×10^{-13}	6.4×10^{-14}	3.8×10^{-14}	2.5×10^{-13}	2.5×10^{-13}
1.0×10^7	3.4×10^{-13}	2.2×10^{-13}	3.2×10^{-13}	2.5×10^{-13}	1.8×10^{-13}	1.4×10^{-13}	9.6×10^{-14}	5.6×10^{-14}	3.4×10^{-14}	2.2×10^{-13}	2.1×10^{-13}
3.0×10^7	2.6×10^{-13}	1.9×10^{-13}	2.6×10^{-13}	2.1×10^{-13}	1.5×10^{-13}	1.2×10^{-13}	8.6×10^{-14}	4.7×10^{-14}	2.9×10^{-14}	1.9×10^{-13}	1.5×10^{-13}
SMh/μ (metric units)	Values of B in metric units										
1.5×10^6	2.2×10^{-12}	1.1×10^{-12}	1.8×10^{-12}	1.3×10^{-12}	7.7×10^{-13}	5.4×10^{-13}	3.6×10^{-13}	2.4×10^{-13}	1.4×10^{-13}	1.1×10^{-12}	1.0×10^{-12}
2.0×10^6	1.6×10^{-12}	8.2×10^{-13}	1.4×10^{-12}	1.1×10^{-12}	6.6×10^{-13}	4.8×10^{-13}	3.2×10^{-13}	2.0×10^{-13}	1.2×10^{-13}	8.2×10^{-13}	8.7×10^{-13}
4.0×10^6	1.0×10^{-12}	6.2×10^{-13}	9.7×10^{-13}	7.7×10^{-13}	5.1×10^{-13}	3.8×10^{-13}	2.6×10^{-13}	1.6×10^{-13}	9.7×10^{-14}	6.2×10^{-13}	6.5×10^{-13}
8.0×10^6	8.2×10^{-13}	5.4×10^{-13}	7.7×10^{-13}	5.9×10^{-13}	4.4×10^{-13}	3.4×10^{-13}	2.4×10^{-13}	1.4×10^{-13}	8.6×10^{-14}	5.4×10^{-13}	5.2×10^{-13}
2.0×10^7	2.6×10^{-13}	4.8×10^{-13}	6.5×10^{-13}	5.2×10^{-13}	3.8×10^{-13}	2.9×10^{-13}	2.2×10^{-13}	1.2×10^{-13}	7.3×10^{-14}	4.8×10^{-13}	3.7×10^{-13}

SOURCE: Catalyst Handbook, Springer-Verlag, New York Inc., Wolfe Scientific Books/London-England, 1970

TABLE C-3

MOLECULAR WEIGHT/VISCOSITY RATIOS

Some values of molecular weight/viscosity are given for typical gas streams. For most duties the accuracy of these values is adequate for the evaluation of pressure drop

Duty	M	M/μ (ft lb h units)	M/μ (metric units)
Primary reformer	15	190	460
Secondary reformer	16	150	360
HT CO shift	16	290	700
LT CO shift	16	370	890
Methanation (NH_3 plant)	8·6	200	480
Methanation (H_2 plant)	2·4	70	160

SOURCE: Catalyst Handbook, Springer-Verlag, New York Inc., Wolfe Scientific Books/London-England, 1970

TABLE C-4

5kW NEAT METHANOL REFORMER DESIGN PARAMETERS

ANNULAR REGION	INTERNAL COMBUSTION	VAPORIZER	REFORMER	EXTERNAL COMBUSTION I	EXTERNAL COMBUSTION II
Tube O.D. (inch)[1]	5.5 5.95	5.95 6.40	6.40 7.75	7.75 8.10	8.10 8.75
Wall (inch)	.025 .025	.025 .025	.025 .025	.025 .025	.025 .025
Tube I.D. (inch)[2]	5.45 5.90	5.90 6.35	6.35 7.70	7.70 8.05	8.05 8.70
Annulus (inch)	0.20	0.20	0.65	0.15	0.30
Cross Sectional Area (ft^2)	0.028	0.030	0.100	0.026	0.055
Surface Area [3] (ft^2)	3.12	3.12 3.35	3.35 4.06		
Surface Area [4] (ft^2)				3.04 3.18	3.18 3.44
Mass Flow					
4 kW ($lb/hr\ ft^2$)	2286	2141	531	2490	1170
7.25 kW ($lb/hr\ ft^2$)	2620	2454	582	2853	1341
Gas Velocity					
4 kW (ft/sec)	41	37	9.2	45	21
7.25 kW (ft/sec)	42	42	9.3	46	22
Heat Transfer h empty ($Btu/Hr\ ft^2\ ^oF$)	4.35	3.44	3.21	4.26	.2
Δp (inches of water)	0.2	0.2	4.0	0.24	0.03

1 Tube O.D. of inside and outside tube defining each annulus
2 Tube I.D. of inside and outside tube defining each annulus
3 Based on 2 ft high active area of internal annuli
4 Based on 1.5 ft high active area of combustion annuli I and II

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APPENDIX D

HEAT TRANSFER CALCULATIONS

HEAT TRANSFER CALCULATIONS

In order to evaluate the heat transfer characteristics of the combustion tube and vaporizer components, heat transfer coefficients were determined based on two correlations. The Leva cooling correlation was used for the combustion tube, and the Beek correlation was used for the vaporizer.

The heat transfer coefficients predicted by the Leva cooling correlation for a packed tube was calculated at part load and full load conditions. This coefficient was then converted to an "empty tube" coefficient by using a factor developed by Colburn. The empty tube coefficient was compared to the effective heat transfer coefficient actually obtained. The results indicated that the effective heat transfer obtained was lower than the predicted empty tube coefficient. Tables D-1 and D-2 depict the correlation and results obtained. A plot of the Nusselt number and heat transfer coefficient versus the Reynolds number in Figure D-1 indicates that improvements in heat transfer can be obtained by increasing the Reynolds number. However, this improvement is obtained at a pressure drop penalty, since pressure drop also increases with the Reynolds number.

The heat transfer in the vaporizer was also evaluated by using the Beek correlation. Here too, a packed tube coefficient was calculated first, and an empty tube coefficient was derived from the packed tube coefficient. The correlation used, and the coefficient obtained are illustrated in Tables D-3 and D-4. The data was also plotted in Figure D-2. Here too, an increase in heat transfer rates can be observed as the Reynolds number increases.

Figure D-3 shows some typical levels of heat transfer coefficients. Although specific conditions, such as temperature, velocity, and geometry affect the heat transfer coefficients, the figure presents some typical values of h for the

purpose of comparison. The h obtained experimentally falls between the h for atmospheric natural convection of air and forced convection of air.

The heat duty desired for heat transfer from the combustion tube to the vaporizer is 9072 BTU/hr. The actual heat transfer obtained was 2961 BTU/hr. Therefore, an increase in heat transfer by a factor of 3 was required. This necessitated a design modification which would provide additional heat transfer to meet the requirement.

TABLE D-1

LEVA COOLING CORRELATION

$Nu_T = 3.5\ e^{(-4.6\ D_p/D_T)}\ Re_p^{0.7}$

Nu_T = Nusselt Number hDt/k

h = Heat Transfer Coefficient

D_t = Hydraulic Diameter of Combustion Tube

k = Thermal Conductivity of Gas

Re_p = Reynolds Number $D_p\ G/\mu$

D_p = Particle Diameter

G = Mass Flow Rate/Cross Sectional Area of Combustion Tube

μ = Viscosity of Gas

TABLE D-2

COMBUSTION TUBE HEAT TRANSFER COEFFICIENTS

FLOW	THEORETICAL PACKED TUBE (1) HEAT TRANSFER COEFFICIENT (BTU/Hr $Ft^2{}^oF$)	THEORETICAL EMPTY TUBE (2) HEAT TRANSFER COEFFICIENT (BTU/Hr $Ft^2{}^oF$)	EXPERIMENTAL (3) HEAT TRANSFER COEFFICIENT (BTU/Hr $Ft^2{}^oF$)
4 kW	103	13	8
7.25 kW	108	14	

NOTES:

(1) 1 3/16 INCH DIAMETER TUBE WITH 3/16 DIAMETER PACKING - USING LEVA COOLING CORRELATION

(2) BASED ON RATIO BETWEEN HEAT TRANSFER COEFFICIENT FOR PACKED TUBES AND EMPTY TUBES DEVELOPED BY COLBURN.

(3) USING Pt MONOLITH AND 4 3/8 INCH LONG Pt PELLET BED.

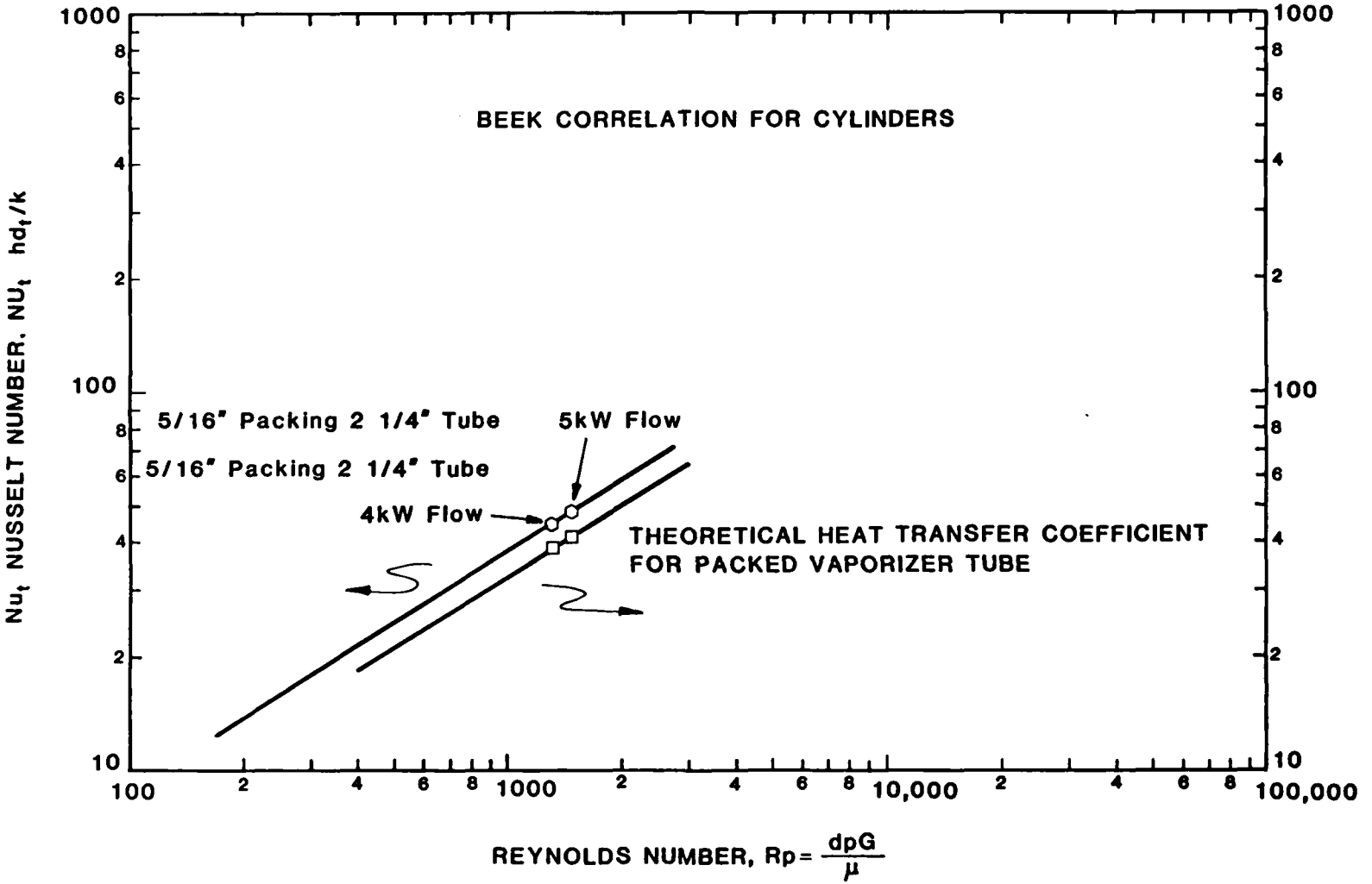


FIGURE D-1

VAPORIZER HEAT TRANSFER CORRELATION

TABLE D-3

BEEK CORRELATION FOR CYLINDERS

$$Nu_t = \frac{Dt}{D_p} \left(2.58\ Re_p^{.33}\ Pr^{.33} + 0.094\ Re_p^{.8}\ Pr^{.4}\right)$$

Nu_t = Nusselt Number hD_t/k

h = Heat Transfer Coefficient

D_t = Hydraulic Diameter of Annulus

k = Thermal Conductivity of Gas

Re_p = Reynolds Number $Dp\ G/\mu$

Dp = Particle Diameter

G = Mass Flow Rate/Cross Sectional Area of Annulus

μ = Viscosity of Gas

Pr = Prandtl Number $\frac{\mu C_p}{k}$

C_p = Heat Capacity of the Gas

TABLE D-4

VAPORIZER HEAT TRANSFER COEFFICIENTS

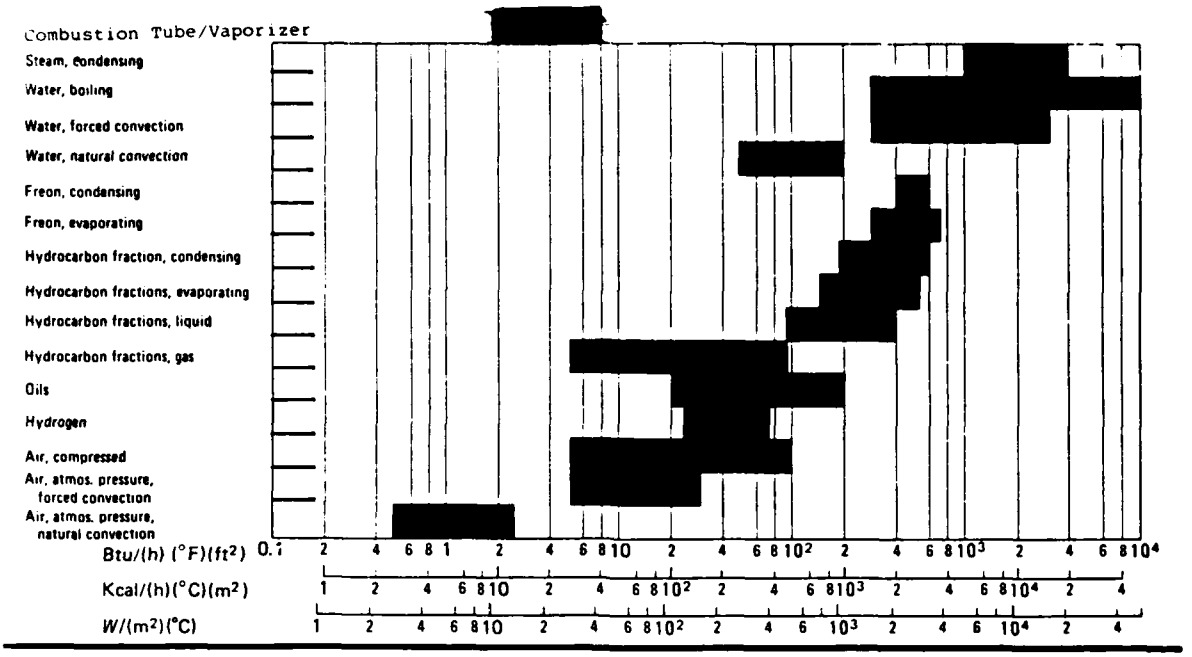
FLOW	THEORETICAL PACKED TUBE (1) HEAT TRANSFER COEFFICIENT (BTU/Hr $Ft^2{}^oF$)	THEORETICAL EMPTY TUBE (2) HEAT TRANSFER COEFFICIENT (BTU/Hr $Ft^2{}^oF$)	EXPERIMENTAL (3) HEAT TRANSFER COEFFICIENT (BTU/Hr $Ft^2{}^oF$)
4 kW	39	5	8
7.25 kW	42	5.3	

NOTES:

(1) 1 3/16 O.D./2.12 INCH I.D. ANNULUS WITH 5/16 INCH PACKING USING BEEK CORRELATION.

(2) BASED ON RATIO BETWEEN HEAT TRANSFER COEFFICIENT FOR PACKED TUBES AND EMPTY TUBES DEVELOPED BY COLBURN.

(3) USING Pt MONOLITH AND S/S SHAVINGS AS PACKING.



Approximate values of *h*, fluid-to-surface heat-transfer coefficients

FIGURE D-2

APPROXIMATE VALUES OF HEAT TRANSFER COEFFICIENTS

SOURCE: Process Heat Exchange, Edited by Vincent Cavaseno and the staff of Chemical Engineering McGraw Hill Publication Co., New York, NY page 101, 1979.

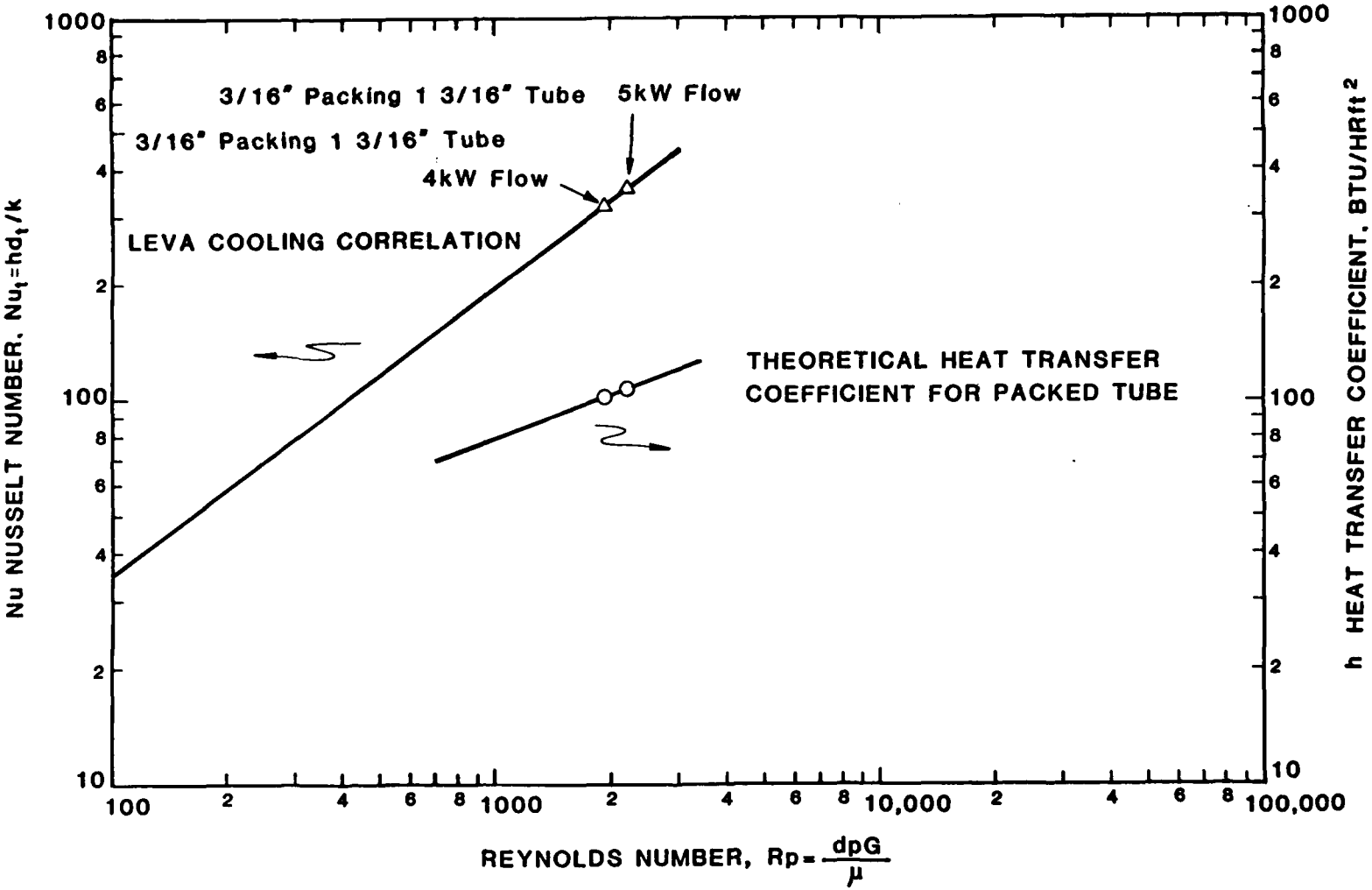


FIGURE D-3

COMBUSTION TUBE HEAT TRANSFER CORRELATION

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